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The Fatigue Problem in Shipbuilding in the Light of New Investigations

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Read in London at a meeting of the Royal Institution of Naval Architects on April 24, 1975, Mr A. J. Johnson, B.Sc., Ph.D (Fellow) in the Chair.

SUMMARY: The problem of fatigue in shipbuilding is discussed from both the consideration of loads and experimental results. It is argued that the way data on the cyclic loading of ships are commonly presented is not optimum from a fatigue point of view. For instance the usual neglection of mean stresses is not justified.

This has come out of a co-operative research effort carried out in five European countries. The principal aim of that investigation was to gather information about the relative fatigue strength of welded structures made of higher strength steels and mild steel.

The main aspect that has been studied was crack propagation.

1. INTRODUCTION

In 1967 the RINA published a paper on fatigue investigations with large structural components carried out on the 1000 tons tensile-compression machine of the Delft Ship Structures Laboratory(1). The main purpose of that work was to provide ship designers and classification societies with realistic fatigue data. For that reason the specimens contained severe discontinuities and the welding was of average shipbuilding standard, (see Figs. 6 and 14). The material was mild steel.

In the course of years ships became bigger and faster and acquired large deck openings. Fatigue cracking developed into a primary problem(2). The application of higher strength steels did not improve the situation. On the contrary, the weight reductions allowed by classification societies when these steels were used were probably too optimistic from a fatigue point of view. Many literature references can be quoted in support of this statement, (see Section 4). Yet for many people in practice the picture is not so clear because there exist also experimental results which seem to be favourable for higher strength steels. That these results are often not relevant for ships is not always understood. Some five to ten years ago classification societies were also confused by the conflicting literature. They expressed differing opinions on the matter(3,4). Ref. 5 was much criticised by fatigue specialists. Practical experience forced some classification societies to correct their over-optimistic rules.

In 1969 the German Ship Research Centre (FDS) and Germanischer Lloyd—aware of the need for realistic experiments—asked the Delft Ship Structures Laboratory to follow up their earlier investigations(1,6). The intention was that the experiments should be repeated, but with specimens made of St. 52. Because of the high costs involved contacts were also made with the Ship Research Centres of Belgium, France, Germany and Holland. They agreed to support financially a co-operative research effort. In addition, the European Community for Carbon and Steel (CECA) would make a considerable contribution. This allowed a more general and fundamental approach to the problem of fatigue in shipbuilding. A research programme (7) was offered to the CECA Commission 'Fatigue et Constructions Types' (Chairman R. Salkin) and was accepted. The responsibility for the co-ordination of the experimental work in the various laboratories and the elaboration of all experimental results was given to the first author of this paper. Mr J. J. L. Van Maanen (CEBERENA) was responsible for the administrative and financial affairs.

In Belgium the experiments have been carried out in the Laboratory for Strength and Welding Technology of the University of Ghent by Mr de Lembre, (Director Professor W. Soete).

In Italy the work was done in the 'Istituto Policattedra di Ingegneria Navale' of the University of Genoa (Professors Marsich and Tedeschi). Due to delays during outfitting of the laboratory the results of the work concerned could not be included in this paper. For this reason the Italian results and also the corresponding part of the investigations carried out in Belgium (bending of longitudinals) will be reported in the near future.

In Germany, Professor S. Weiss (FDS) and Professor H. Petershagen supervised the experiments carried out in the Shipbuilding Laboratory of the University of Hamburg by Dipl Ing H. Paetzold.

In France Mon M. Jourdain, Directeur Général de l'IRCN, and Mon E. Castellan contracted the Laboratory of the French Navy for their part of the programme which was realised by Mon Peyrat.

In Holland Ir W. Spuyman, and Ir Th. Lahr (NSS-TNO) maintained the necessary contacts with the Delft Ship Structures Laboratory.

A special word of thanks is due to Messrs J. van Lint, R. T. van Leeuwen, R. Vonk and B. van' Triest of the Delft Ship Structures Laboratory for the careful elaboration of a large quantity of experimental results.

It is not the aim of the present paper to give a full account of the results and conclusions of the co-operative research effort. For that the reader is referred to Ref. 8. For this Institution it was thought to be more appropriate to give a

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general discussion about the fatigue problem in shipbuilding, and highlight some particularly important or controversial aspects. Among the latter are the role of mean stresses in connection with constant amplitude and programmed loadings; the prediction of fatigue life of ship structural details with the aid of unwelded notched plate specimens; the value of fracture mechanics for the evaluation of test results and for the calculation of fatigue life; the value of rules for life estimates such as that due to Palmgren-Miner; the danger of fatigue cracks in ships and last but not least the advantage of using higher strength steels in relation to fatigue.

2. STATE OF AFFAIRS

2.1 Historical

For many years shipbuilders have shown little interest in fatigue problems. In 1962 Yuille succeeded in bringing the matter to the surface with a pertinent RINA paper(9). The essence of his reasoning was: 'Do fatigue cracks develop in ships or not? If not, it has no sense to measure all wave-induced stresses. For then only the highest absolute values of stress are of interest in connection with the strength of ships'.

With the aid of Fig. 1 Yuille tried to demonstrate that indeed ships are not in danger of fatigue. It does not invalidate the great merits of his paper when it is said that the figure was not absolutely convincing. The load data belonged to the OCEAN VULCAN, being a ship of rather conservative design. The fatigue test data were not very accurate. (This was not Yuille's fault. Only very few data on the fatigue behaviour of structures were available). Yuille's argument that in the OCEAN VULCAN fatigue cracks had never developed, was offset by Vedeler's information(10). Once 129 cracks had been observed in a 4½ year old tanker.

In order to clarify the matter Nibbering(11) made use of Bennet's data on longitudinal wave bending of two fast dry cargo ships, the CANADA (9085 tons dwt; 19·5 knots) and the MINNESOTA (7260 tons; 19 knots(13,14). He corrected the frequency distribution of the longitudinal wave bending stresses for:

(a) slamming and whipping, (see Fig. 2);
(b) changes in temperature and loading condition;

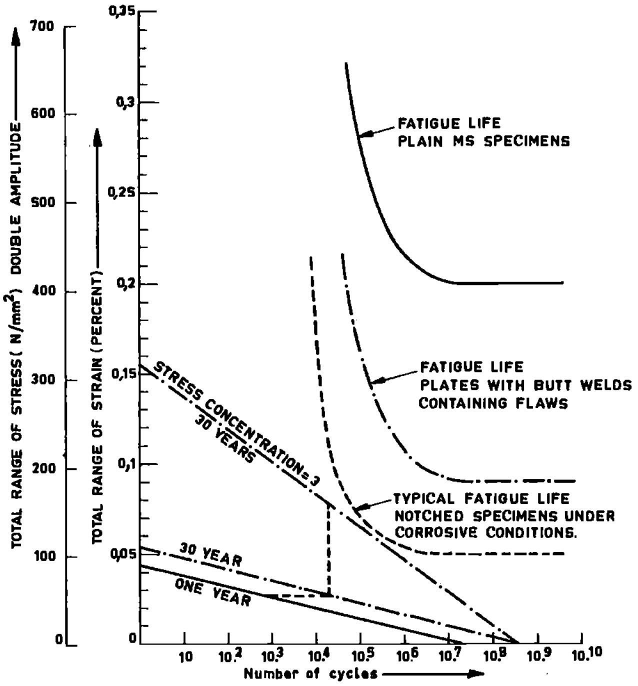


Fig. 1 Diagram According to Yuille(9)

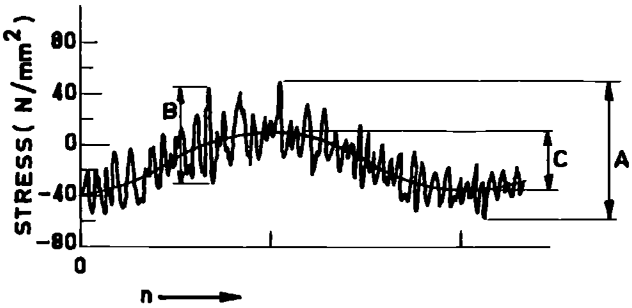


Fig. 2 Increase in Range of Wave Bending Stresses (C). Due to Slam-Induced Vibrations

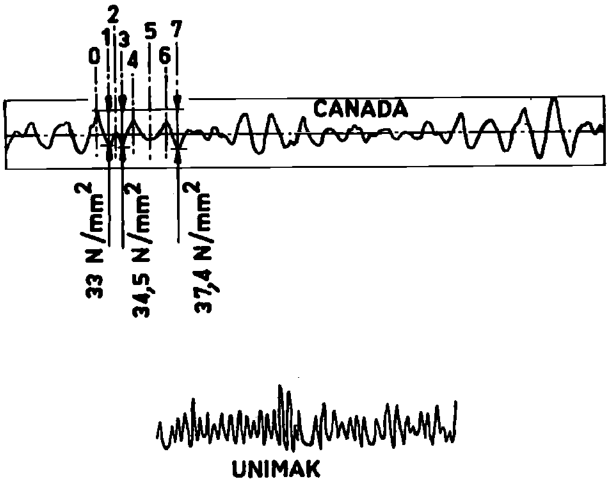


Fig. 3 Example of Dependency of Magnitude of Cyclic Stress on Choice of Successive Peaks

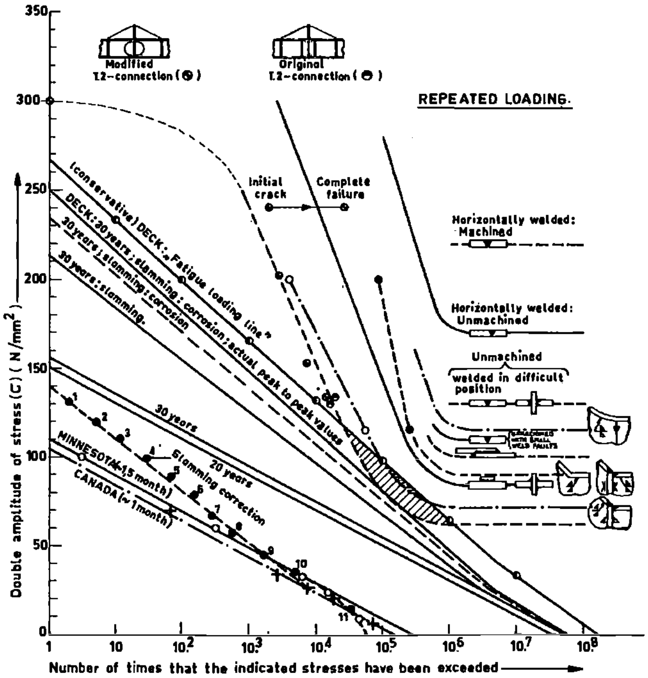


Fig. 4 Comparison of the Cyclic Loading of a Ship with Fatigue Data for Welded Details(11)

(c) changes in water pressure on the bottom;
(d) influence of corrosion;
(e) actual peak to peak values, (see Fig. 3).

He also converted the cumulative frequency distribution into a line each point of which represented the complete load history of the ships. For these fast ships the correction for slamming proved to be very important, (Fig. 4). At that time the first results of axial fatigue experiments with mild steel tanker longitudinals had become available. When they were compared with the deck 'fatigue loading line', (Fig. 4), it was evident that fatigue cracks might occur. Yet the outcome was not too pessimistic, for the structures tested incorporated severe discontinuities (Figs. 6, 14), and even with these only small cracks could develop.

2.2 Danger of fatigue cracks

The only unknown was whether small fatigue cracks are dangerous from a brittle fracture point of view. In this connection it is important that cracks always develop at weld defects (undercuts, lack of penetration etc.). As welding generally impairs the notch ductility of the parent metal, the danger of brittle fracture may be real as long as the tip of a fatigue crack is situated in the welded region. It may be concluded that for modern ships, made of excellent fine grain steels, small cracks are often more dangerous than long ones. The scope of this paper does not permit a thorough discussion of this important point. The reader is referred to Ref. 1 and to Fig. 5 of Ref. 12. The earlier mentioned mild steel bottom longitudinals (1) indeed fractured in a brittle manner at temperatures below −10°C and at nominal stresses equal to 2/3 of yield stress. In contrast to this the specimens of St. 52 discussed in the present paper all fractured only after extensive deformation.

The nominal stresses exceeded the yield point at temperatures as low as −30°C. Consequently when proper steels and welding methods are used fatigue cracks are not dangerous provided that they are not too long. The critical crack length for shear fracturing can be easily calculated with the aid of fracture mechanics. Mostly it is in the order of magnitude of several metres!

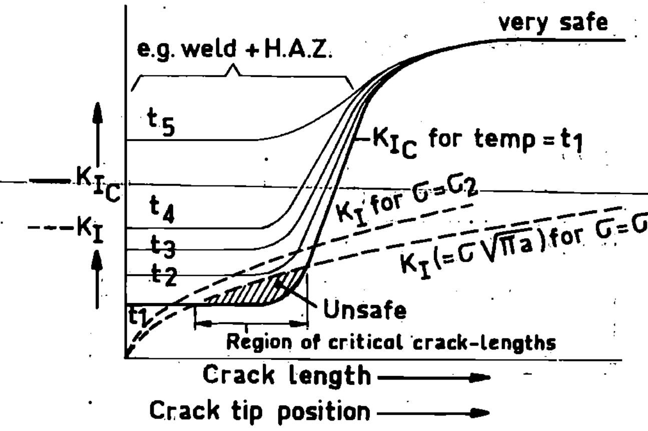


Fig. 5 Relative Importance of Crack Length and Crack Position in Welded Region (12)

An example of a dangerous situation despite the use of steels with excellent notch toughness is given in Ref. 12. Complete brittle fractures developed in the HAZ (heat affected zone) of electro-gas welded 34 mm thick plates when they were subjected to fatigue loading at −15°C. Critical crack lengths were in the order of the plate thickness.

2.3 The crack initiation-propagation dilemma

In ships there are hundreds of kilometres of welds and many thousands of weld crossings. Although non-destructive testing is widely applied, weld defects will nevertheless be present in ships. Some will be too small to detect; others escape notice because of their unfavourable position and orientation. Many defects are sharp notches. When locally the cyclic stresses are high enough, fatigue cracks will often start growing after a relatively small number of cycles. In the structural specimens of Fig. 14 at 200 N/mm^2 a crack started after 1600 cycles, reached a length of 4 mm after 8500 cycles and 20 mm after 20,000 cycles. In Figs. 11 and 12 the mechanically notched plate DH 19 had a 1 mm crack after 8000 cycles and a 20 mm one after 40,000 cycles. The growth from 1 to 20 mm took 32,000 cycles. The logarithms of 40,000 and 32,000 are practically equal: 4·6 and 4·5. Consequently neglection of the number of cycles necessary for the initiation of the crack hardly influences the position of the Wöhler-curves for 20 mm crack length.

From the foregoing the conclusion may be drawn that for shipbuilding, experimental data about the resistance of structures to crack propagation are of primary interest. The advantage of neglecting the initiation time is that the influence of a number of difficult-to-grasp parameters is excluded (scatter!). Furthermore calculations of crack growth under constant and variable cyclic load conditions can be made with more confidence than the calculation of life time up to crack initiation. For many it will be attractive that such an approach is on the safe side.

It should be emphasised that the approach is only advocated for structural details which are frequently found in ships. For these, expensive and time-consuming measures in order to increase the resistance to crack initiation will generally not be justified. But for structural details which are not numerous such as hatch corners of container ships and bulk carriers, measures to improve the fatigue strength pay greatly.

High quality welding and post-weld treatments may result in considerable benefits. One need not only consider grinding and planing. Undercuts are also highly improved by TIG welding or by peening, see Hotta et al (15); Kanazawa (20); Gurney (17) and Reemsnyder (18). Takahashi (16) observed an increase in fatigue strength of submerged arc welds from 160 to 320 N/mm^2 (repeated loading) due to TIG welding of the undercuts. Harrison et al (19) found an increase from 110 to 260 N/mm^2. Deep grinding proved to be far more expensive than peening and TIG welding.

Sometimes it is wrongly stated that these improvements have little effect. The argument is that for welded redundant structures such as ships 90% of the fatigue life of a structural detail consists of crack propagation. But this is only true in the case of every day workmanship. Fig. 4 gives an idea of how much may be gained by machining of butt welds. A most successful approach is to improve the endurance limit so much that cracks simply are not able to initiate; then double amplitudes of stress in the order of magnitude of 200 N/mm^2 (repeated loading) may be tolerated millions of times instead of a few 100,000 times. It makes the difference between no cracking during the ship's lifetime or cracking after one year. Ships of the first type (with excellent structural details) should be considered as 'safe-life' structures. For when, despite great care, a crack starts after many years, it will propagate quickly. The cause is that the material in the line of the crack path will have been damaged by the previous large number of load cycles.

This contrasts with the case when cracks start early in the lifetime. Then the surrounding material is still relatively sound and the crack propagates slowly. It can be detected in time and repaired; the structure is 'fail-safe'. Apart from this, it is a general rule that the milder the stress concentration in a structure, the smaller the number of cycles for crack propagation will be in relation to total lifetime and vice versa. If the bar DH 19 discussed previously had a semi-circular notch instead of a saw-cut, a crack would only have started after some 70,000 cycles. The growth from 1 to 20 mm would have taken less than 32,000 cycles, making at the maximum 102,000 cycles in total. Only 33% of this number has been spent for propagation, while for the sharply notched bar it was 32,000 ÷ 40,000 = 80%.

2.4 Load-presentation and cumulative damage

The type of presentation in Fig. 4 becomes far more complicated when it concerns structures such as the hatch corners of modern ships. For these, the vertical longitudinal wave bending is no more the dominant type of loading.

Torsion, horizontal bending and transverse loads have become equally important. When static strength is considered it is logical to look for the most unfavourable combination of the various load components. But for fatigue strength the number of times that various possible combinations occur is important. These frequency distributions are difficult to estimate. The reader is referred to work of Meek and co-workers(2) and a paper of Alte(22) for more information.

Cyclic stress data for structural discontinuities can also be obtained with the aid of strain gauges at critical points. This method has the advantage that the combined effect of the external load components becomes known. But the problem remains of how to use that information for the prediction of the fatigue behaviour; Figs. 13, 20 and 21 of this paper are of some help. It can be seen that the endurance of relatively complicated structures such as conservative tanker longitudinals correlates rather well with that of simpler models if plotted on the basis of local strains. When it is realised that the stress state in the different types of specimens was very different the result is satisfying; it could hardly be improved by applying fracture mechanics, (Figs. 17, 18). Of course the correlations have been obtained for constant amplitude loading, but it is not unreasonable to expect similarly good results for service-conforming loading. Favourable experiences with strain gauges have also been reported by Gassner and Haibach(23).

Wave induced stresses in ships are commonly presented as cumulative frequency distributions (Figs. 1, 4). This may be the most convenient way for load experts, but it is certainly not what fatigue experts prefer. Figs. 2 and 3 illustrate two relevant aspects. Another, the influence of changes of mean stresses (still water stresses) is equally important, (see Sections 6 and 7). Apart from this, fatigue specialists are still in difficulties when asked to predict the fatigue behaviour of a ship for which frequency distributions of loads are available.

Some still dream of finding a rule such as that due to Palmgren-Miner for estimating the fatigue life of a ship with the aid of results of constant load tests. Others rely upon results of programmed load tests, while the more pessimistic require service-conforming loading preferably with prototypes!

It will be seen in Section 7 that what is indispensable for aeroplane building (and payable!) is not absolutely necessary for shipbuilding.

This section ends here although the state of the art is not yet sufficiently developed. However, other important aspects, for example fatigue strength of higher strength steels, influence of mean stresses and procedures for estimating the fatigue life of a ship are so closely connected to the co-operative research work that they will be discussed in the separate Sections 4, 5, 6 and 7.

3. DESCRIPTION OF THE CO-OPERATIVE RESEARCH PROGRAMME

The essentials for the choice of test specimens and test procedures were as follows:

(a) In order to obtain realistic results the greater proportion of the specimens should be structural specimens, preferably of large size. They should incorporate typical structural discontinuities, Fig. 6.

(b) For reasons of economy in costs and time they should be comparable to those tested in the Delft Ship Structures Laboratory in the early sixties, (Fig. 14) which were loaded with P min/P max $= -\frac{1}{2}$.

(c) In order to allow a scientific anlysis of the results of the large structural specimens, smaller ones of simplified form should be included in the programme (Fig. 13), (Model family).

(d) For the same reason, elementary, non-welded specimens containing saw-cut notches had to be included, (Figs. 10 and 11).

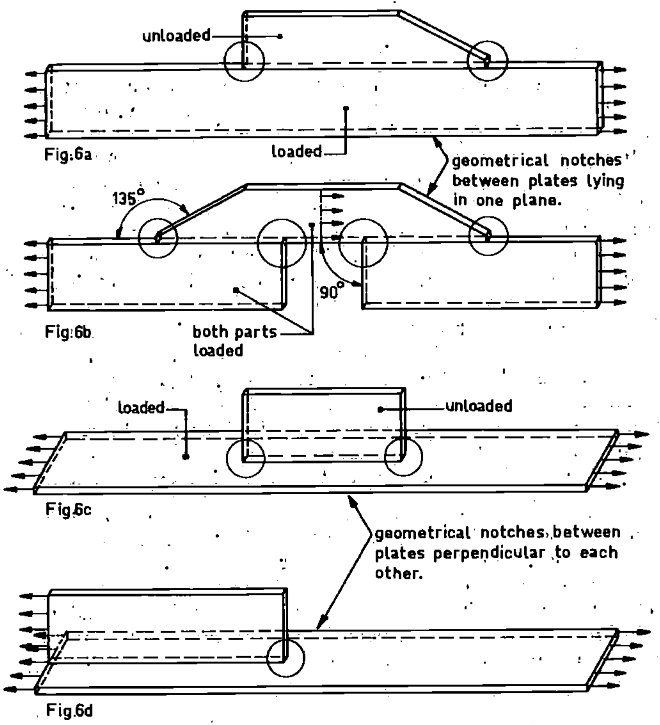
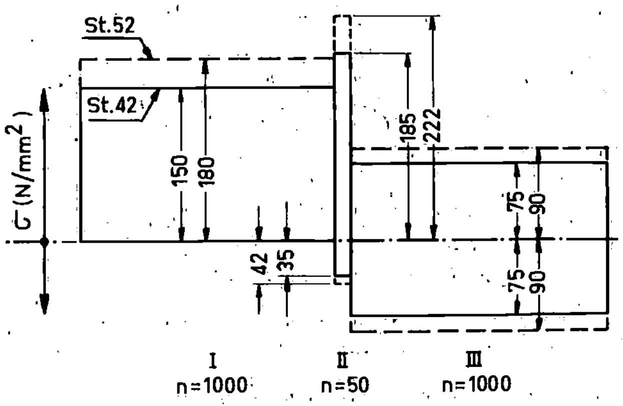
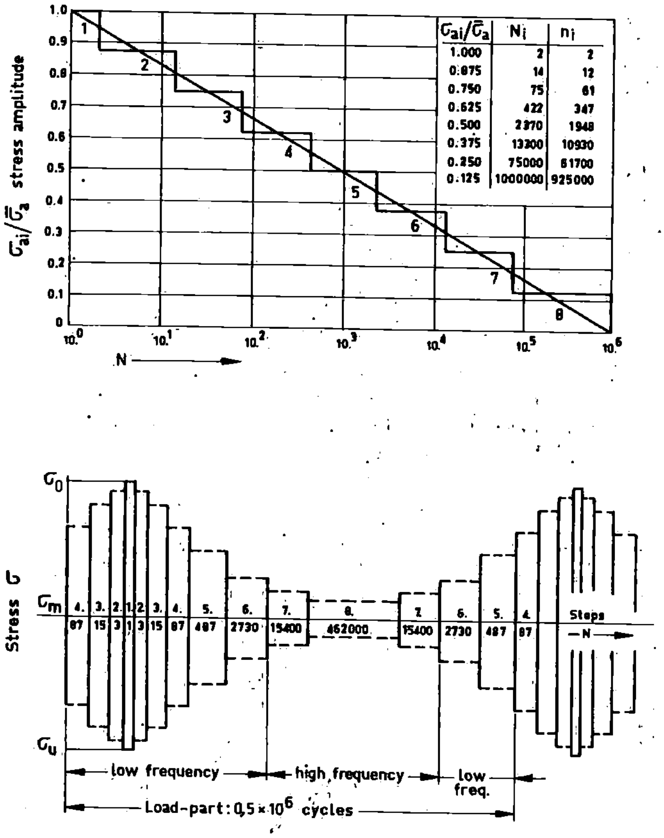


Fig. 6 Typical Structural Discontinuities



Sequence of load groups						
1	2	3	4	5	6	1
I	I	III	III	II	II	I
II	III	I	II	III	I	II
III	II	II	I	I	III	III

Fig. 7 Three-Stage Load Programme(7)



$\sigma_{ai}/\bar{\sigma}_a$	N_i	n_i
1.000	2	2
0.875	14	12
0.750	75	61
0.625	422	347
0.500	2370	1948
0.375	13300	10930
0.250	75000	61700
0.125	1000000	925000

Fig. 8 Staircase Programme(28)

(e) Because of the characteristics of the available testing facilities, most specimens would be subjected to constant amplitude loading. Yet it was also thought to be essential to obtain some information for programmed loads.

(f) It was agreed that for ship structures, information about the rate of crack propagation was of greater interest than the number of cycles up to crack initiation (see Section 2.3).

Next to the interrupted beam specimen shown in Fig. 14 continuous beams have been tested in Belgium and Italy. The results will be reported separately, because the Italian experiments are not yet finished.

The design of the specimens of Fig. 13 reflects Figs. 6 and 14. In the A-specimens with bracket the horizontal and vertical asymmetry of the Fig. 14 type has been eliminated. The same applies to the B-specimens, containing two 'bottom flanges' where at the same time local bending and twisting, induced by the bulkhead, is limited. The capacity of the testing machine mainly determined the dimensions of the specimens. 52 specimens were available of which 26 were were made of St. 37-42 and 26 were made of St. 52. In France 40 specimens have been tested, half of them subjected to repeated axial loading and the other half to loading with P min/P max = $-\frac{1}{2}$. The remaining specimens will be subjected to programmed fatigue loading in Holland in the near future.

Some of the unwelded notched plate specimens have been subjected to programmed fatigue loading. Two programmes have been applied, the first of which is the simplest but is nevertheless realistic(7). It can be carried out with some difficulty on constant-amplitude testing machines (Fig. 7). The programme has been conceived on the idea that only those parts of a ship which are, on the average, subjected to a tensile mean stress will eventually suffer from fatigue. Therefore the greater part of the programme should be in the tensile range. However, conditions can also be such that in the regions of danger, lower or even compressive mean stresses occur. Therefore they are included in the simplified programme of Fig. 7. Although during that stage crack growth will hardly occur, its effect on later conditions when the mean stress is tensile again may be unfavourable. Thus the programme reflects the alternating conditions of 'fully loaded' and 'ballasted' with incidental extreme weather conditions.

The second programme is shown in Fig. 8(28), and is more sophisticated than the first, but does not include changes in still water stresses. It was thought that just because these two programmes were essentially different, valuable indications about the influence of non-constant loading might be obtained.

Apart from the previously mentioned bending experiments with longitudinals, Belgium was responsible for the so-called routine fatigue tests and the determination of the mechanical properties of the steels used(8). The fatigue tests were more sophisticated than routine experiments, because the crack propagation was carefully followed and reported. The specimens were side notched and subjected to axial alternating and repeated loading and to repeated bending Fig. 11. The results of the experiments, after analysis and elaboration have been presented in several ways, see Ref. 8. Direct comparisons have been made between the results for each type of specimen for St. 42 and St. 52. Where possible, curves have been constructed for 0, 5, 8 and 20 mm crack lengths. All available data have been displayed in such a form that justified comparisons can be made between the results for the various types of specimens. The strain gauge data have been used extensively. The fatigue results for the small specimens have been corrected in such a way that they may be regarded as being representative of specimens of infinite width.

Most data have been elaborated with the aid of fracture mechanics. The aim was to be able to compare all results on the basis of a representative ΔK – value (cyclic stress intensity parameter) and number of cycles for a significant part of the total crack growth, ($N_{8mm} - N_{5mm}$). The choice of the latter is borne out by the fact that for structural specimens plots of da/dn versus ΔK are generally insufficiently accurate. From all these data only the most characteristic have been included in the present paper in order to illustrate tendencies, opinions and weak points.

4. DIFFERENCES IN THE FATIGUE STRENGTH OF MILD STEEL AND HIGHER STRENGTH STEEL

As long ago as 1949 Weck (24) stated that trying to improve the fatigue strength of welded structures by the use of higher strength steels is fruitless. Many references can be cited which confirm this statement, but there are also many which are more optimistic.

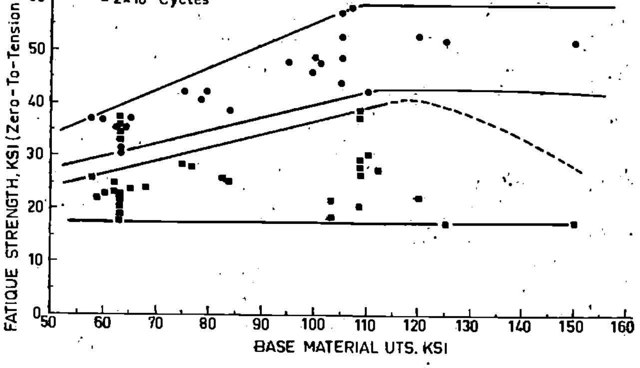


Fig. 9 Effect of Base Metal UTS on Weld Fatigue Strength for Transverse Butt Welds Tested under Pulsating Loading (R = 0)(25)

Fig. 9 from Ref. 25 by Munse and La Motte Grover illustrates the situation. For 2 x 10^6 cycles the upper line is even too optimistic. When the single result at 35 KSI and 110 KSI UTS is neglected, all data fall between 16 and 28 KSI. This is about the scatter width for mild steel. For 10^5 cycles the picture is clearly better.

Gurney(17) found little or no advantage for 10 higher strength steels with UTS from 430 to 750 N/mm^2 when used for non-load carrying fillet welds, (pulsating tension).

Fisher et al(26) carried out nearly 400 bending tests on welded beams for 3 grades of steel. He concluded that 'steels with yield points between 250 and 700 N/mm^2 did not exhibit any significant difference in fatigue strengths'.

What is the reason that an increase in static strength is not accompanied by an increase in cyclic strength? In this paper we cannot do more than give some explanation. At the tip of a fatigue crack, cyclic elastic + plastic straining occurs. As a first approximation the plastic deformation energy per cycle, being the product of local stress and plastic strain, may be thought to be responsible for the fatigue damage of the material at the crack tip. Comparing steels of different strengths the local stresses will be higher and the local plastic strains smaller, the stronger the steel. The product of both will be more or less the same, independent of yield point (strain energy history per cycle). The capacity of various steels for absorbing cyclic deformation energy is also more or less constant, since a high strength steel has a lower ductility than a low strength steel. As both energy history per cycle and capacity are more or less independent of yield point, the same will apply to the number of cycles to cracking.

In welded structures the residual stresses must also be considered. They will be higher the higher the yield point. This may have an adverse effect, especially in the early stages of crack development. A final aspect is that the welding of higher strength steels requires more care than that of mild steel. In this connection Harrison (19) may be quoted:'Small sharp defects at the weld periphery, derived from the welding slag (slag intrusions), are responsible for the low fatigue strength of high-yield steels', (see also Ref. 29).

The outcome of the present investigation is in line with the foregoing. There is in general an advantage for St. 52 over St. 42, but it is not spectacular.

Fig. 10 shows the results obtained in Germany. There is a distinct advantage for St. 52 gr. DH36 at high stresses for both P min/P max = 0 and −1. Above some 500,000 cycles St. 42 gr. A behaves better. The German results are for full fracture of the specimens. In Belgium crack growth was recorded which made it possible to construct Wöhler curves for various crack lengths. They have been corrected for the restricted width of the specimens in order to make them directly of use for ships. Both for 1 mm and 20 mm crack length the tendency is similar to that of the German experiments although definitely less pronounced. Taking all the Belgian results together there remains little advantage for St. 52 DH 36, (Figs. 11, 12, 19).

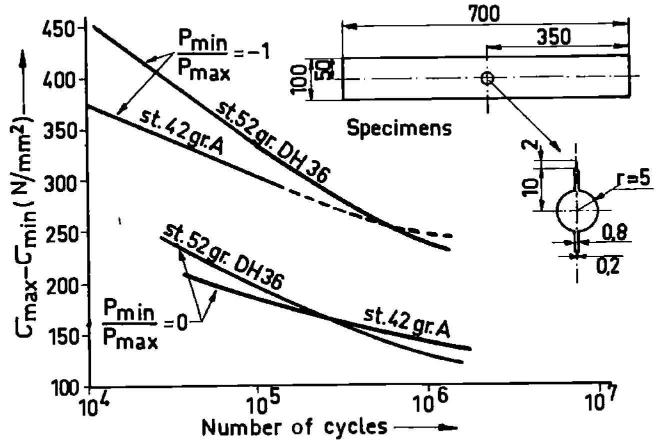


Fig. 10 Results of German Experiments with Centrally Notched Plates under Axial Loading

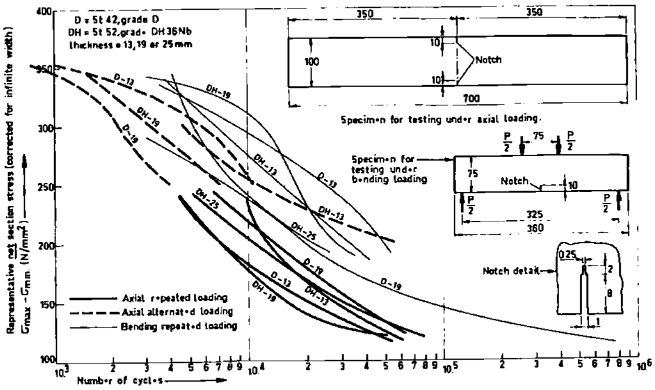


Fig. 11 Wöhler's Curves for Largest Crack Length of 1mm (Belgian Specimens)

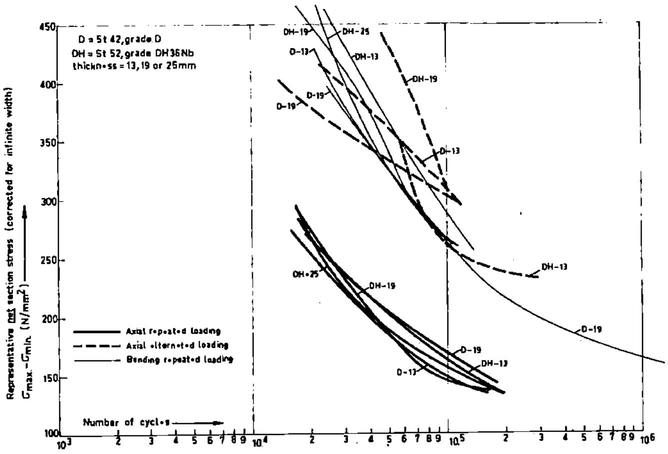


Fig. 12 Wöhler's Curves for Largest Crack Length of 20mm (Belgian Specimens)

The results of the French experiments are even more pessimistic. No difference has been found between St. 42 gr. A and St. 52 gr. DH 36, (Fig. 13). This applies to the results for small and large cracks and to P min/P max = 0 and −½. The Dutch results are better, especially for greater crack lengths, Figs. 14 and 15. The specimens were much larger and more 'structural' than those used in France.

Therefore it is believed that taking all the results together, a 10 to 15% advantage may be obtained by using St. 52. In Section 7.2 it will be explained that this is probably an underestimation. The results of the programmed load tests were far more favourable for St. 52 than for St. 42.

5. CRACK PROPAGATION AND FRACTURE MECHANICS

The Paris-Erdogan law(31):

$$\frac{da}{dn} = C(\Delta K)^m$$

has been generally accepted as an effective tool for the evaluation of results of fatigue crack propagation experiments and for prediction purposes. With the passage of time four aspects have become clear:

(a) m is not constant;
(b) da/dn − K plots consist of three branches instead of one;

(c) m and C are very much influenced by scatter and by inaccuracies of curve fitting;

(d) the type of fatigue testing should be taken into account(32), (constant load, constant strain or constant net stress tests).

The present authors agree with Rolfe and Munse that constant net stress tests are the most realistic. They found a linear relation between da/dn and stress for all stresses and test pieces and for P min/P max = 1 and 0(32). Gurney(34) discovered some dependency of m on the yield point, but Maddox (35) could not confirm this.

Crooker and Lange (33) brought together a lot of experimental results from published literature. For many steels with yield points varying from 350 to 2000 N/mm², most of the m values were between 2·2 and 4·4.

Ref. 35 by Maddox is recommended for further information on the position of the knees of the branches and C and m values. (For welded structures too much refinement in estimating crack propagation laws does not pay because of the difficulty in understanding the influence of residual stresses)(36).

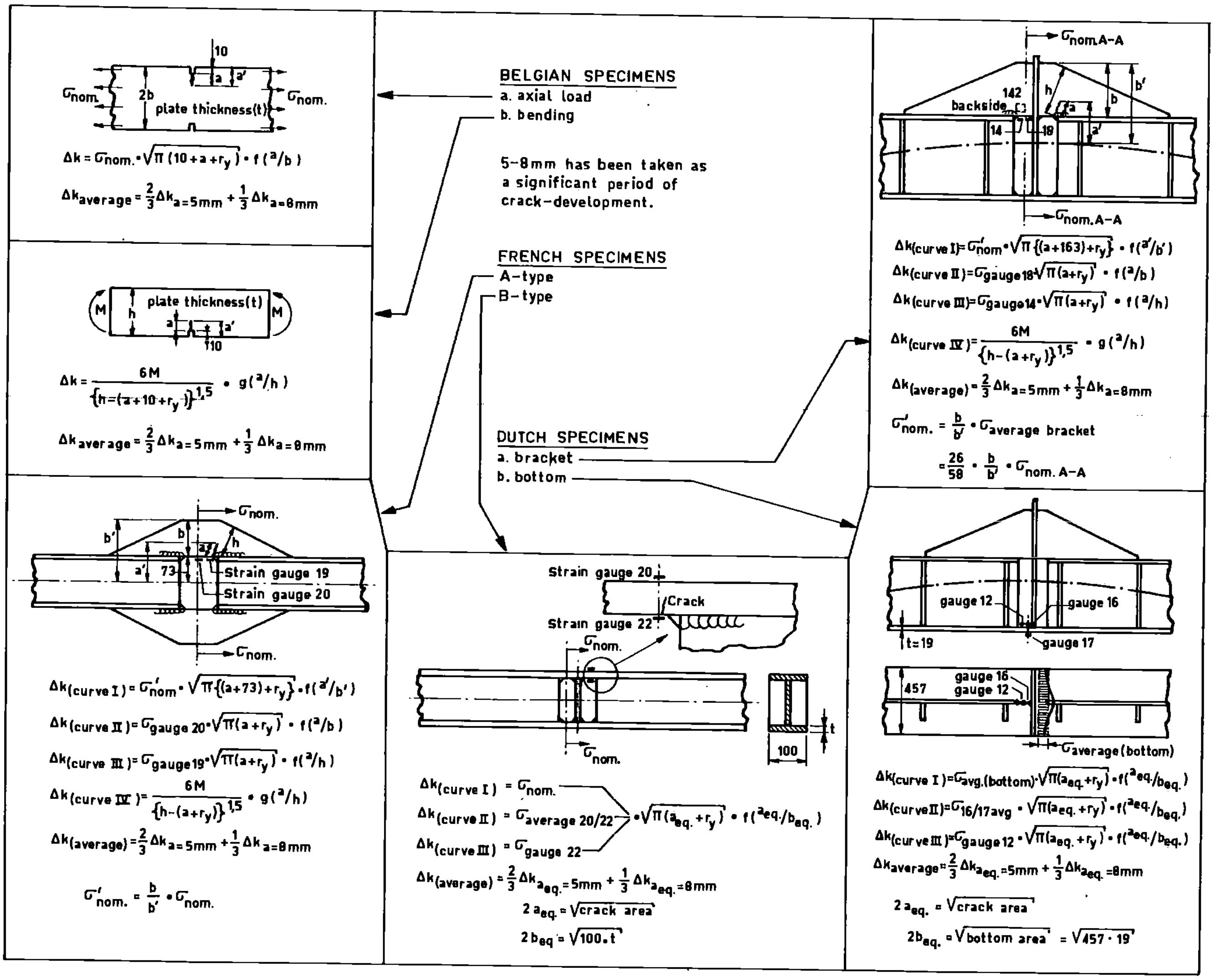
The results of the Belgian experiments have led to m values varying from 3 to 6 for repeated axial loading, and from 1 to 3 for repeated bending loading. But there is no need for great disappointment, since Fig. 16 shows that all results for repeated loading, (two steels, three plate thicknesses), conform extremely well to a linear relation between log C and m. Of interest is that the analysis has been made both by Schrickx in Ghent and Vonk in Delft. The relevant C and m values differed considerably, but all conformed to the one single relation.

During the ISSC 1973 in Hamburg this fortunate result was also mentioned by representatives from Great Britain(46) and Japan(47). It is not surprising that the data for alternating loading in Fig. 16 lie apart. Crack closure during compression is mainly responsible for a relatively slower rate of crack propagation.

The results of the structural specimens could not be adequately analysed by plotting da/dn as function of ΔK. As an alternative, the number of cycles for crack growth from 5 to 8 mm has been plotted as a function of representative ΔK values. The 5-8 mm crack length has been chosen for various reasons. Such small cracks do not change the overall geometry of the structure. The influence of differences in local geometry, i.e. weld shape, undercuts etc. is suppressed. The same applies to the effect of small incidental variations in the rate of crack propagation.

Table I gives a summary of all formulae tried. For the structural specimens several formulae have been directed towards illustrating the value of the particular approach adopted rather than that the authors are convinced of their authenticity. The main reason for the fracture mechanics approach is that we urgently need a method for comparing the results of experiments with notched plates on the one hand and structural specimens on the other.

TABLE I. Summary of Formulae for the Determination of ΔK values.



$$\Delta k = \sigma_{nom.} \cdot \sqrt{\pi\,(10 + a + r_y)} \cdot f(a/b)$$

$$\Delta k_{average} = \frac{2}{3}\Delta k_{a=5mm} + \frac{1}{3}\Delta k_{a=8mm}$$

$$\Delta k = \frac{6M}{\{h-(a+10+r_y)\}^{1,5}} \cdot g(a/h)$$

$$\Delta k_{average} = \frac{2}{3}\Delta k_{a=5mm} + \frac{1}{3}\Delta k_{a=8mm}$$

$$\Delta k_{(curve\ I)} = \sigma'_{nom} \cdot \sqrt{\pi\{(a+73)+r_y\}} \cdot f(a'/b')$$

$$\Delta k_{(curve\ II)} = \sigma_{gauge\ 20} \cdot \sqrt{\pi(a+r_y)} \cdot f(a/b)$$

$$\Delta k_{(curve\ III)} = \sigma_{gauge\ 19} \cdot \sqrt{\pi(a+r_y)} \cdot f(a/h)$$

$$\Delta k_{(curve\ IV)} = \frac{6M}{\{h-(a+r_y)\}^{1,5}} \cdot g(a/h)$$

$$\Delta k_{(average)} = \frac{2}{3}\Delta k_{a=5mm} + \frac{1}{3}\Delta k_{a=8mm}$$

$$\sigma'_{nom.} = \frac{b}{b'} \cdot \sigma_{nom.}$$

BELGIAN SPECIMENS
a. axial load
b. bending

5-8mm has been taken as a significant period of crack-development.

FRENCH SPECIMENS
A-type
B-type

DUTCH SPECIMENS
a. bracket
b. bottom

$$\left.\begin{aligned}\Delta k_{(curve\ I)} &= \sigma_{nom.}\\ \Delta k_{(curve\ II)} &= \sigma_{average\ 20/22}\\ \Delta k_{(curve\ III)} &= \sigma_{gauge\ 22}\end{aligned}\right\rangle \cdot \sqrt{\pi(a_{eq.}+r_y)} \cdot f(a_{eq.}/b_{eq.})$$

$$\Delta k_{(average)} = \frac{2}{3}\Delta k_{a_{eq.}=5mm} + \frac{1}{3}\Delta k_{a_{eq.}=8mm}$$

$$2\,a_{eq.} = \sqrt{crack\ area}$$

$$2\,b_{eq} = \sqrt{100 \cdot t}$$

$$\Delta k_{(curve\ I)} = \sigma'_{nom} \cdot \sqrt{\pi\{(a+163)+r_y\}} \cdot f(a'/b')$$

$$\Delta k_{(curve\ II)} = \sigma_{gauge\,18} \sqrt{\pi(a+r_y)} \cdot f(a/b)$$

$$\Delta k_{(curve\ III)} = \sigma_{gauge\,14} \cdot \sqrt{\pi(a+r_y)} \cdot f(a/h)$$

$$\Delta k_{(curve\ IV)} = \frac{6M}{\{h-(a+r_y)\}^{1,5}} \cdot g(a/h)$$

$$\Delta k_{(average)} = \frac{2}{3}\Delta k_{a=5mm} + \frac{1}{3}\Delta k_{a=8mm}$$

$$\sigma'_{nom.} = \frac{b}{b'} \cdot \sigma_{average\ bracket} = \frac{26}{58} \cdot \frac{b}{b'} \cdot \sigma_{nom.\,A-A}$$

$$\Delta k_{(curve\ I)} = \sigma_{avg.(bottom)} \cdot \sqrt{\pi(a_{eq.}+r_y)} \cdot f(a_{eq.}/b_{eq.})$$

$$\Delta k_{(curve\ II)} = \sigma_{16/17\,avg} \cdot \sqrt{\pi(a_{eq.}+r_y)} \cdot f(a_{eq.}/b_{eq.})$$

$$\Delta k_{(curve\ III)} = \sigma_{gauge\,12} \cdot \sqrt{\pi(a_{eq.}+r_y)} \cdot f(a_{eq.}/b_{eq.})$$

$$\Delta k_{average} = \frac{2}{3}\Delta k_{a_{eq.}=5mm} + \frac{1}{3}\Delta k_{a_{eq.}=8mm}$$

$$2\,a_{eq.} = \sqrt{crack\ area}$$

$$2b_{eq.} = \sqrt{bottom\ area} = \sqrt{457 \cdot 19}$$

The main difficulty is whether a structural specimen such as type A (Fig. 13) should be conceived as a wide plate containing a substantial notch, or as a small plate (bracket) having a very small initial side notch (the undercut of the weld). In the first case the stress to be used for the stress intensity parameter K is the nominal stress; in the second case it is a local stress. How local is something which has to be concluded from the comparisons in Figs. 17 and 18. Generally speaking the various curves II seem to conform best. The position of the strain gauges 2, the output of which has been used as stresses in the particular ΔK formula is such that these have the significance of local 'nominal' stresses. The curves III, for local 'peak' stresses are clearly worse. This is fortunate because it is what would be expected from a fracture mechanics point of view. It is remarkable that curves I, which consider the specimens as a whole, are close to curves II. This could be fortuitous, but it may also be interpreted as an indication that an 'overall' approach is not too sensitive to structural parameters (square notch, triangular bracket, presence of flanges).

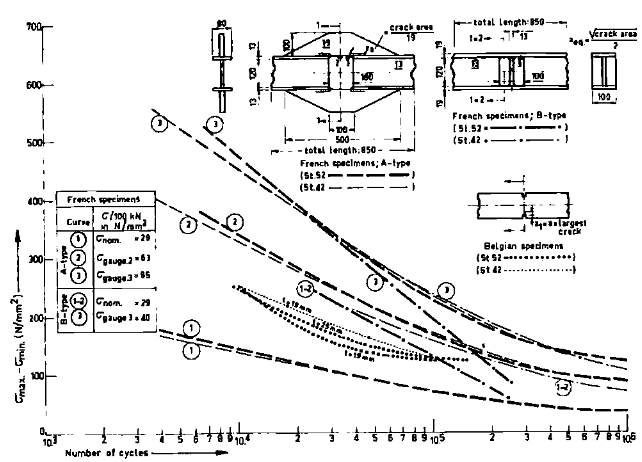
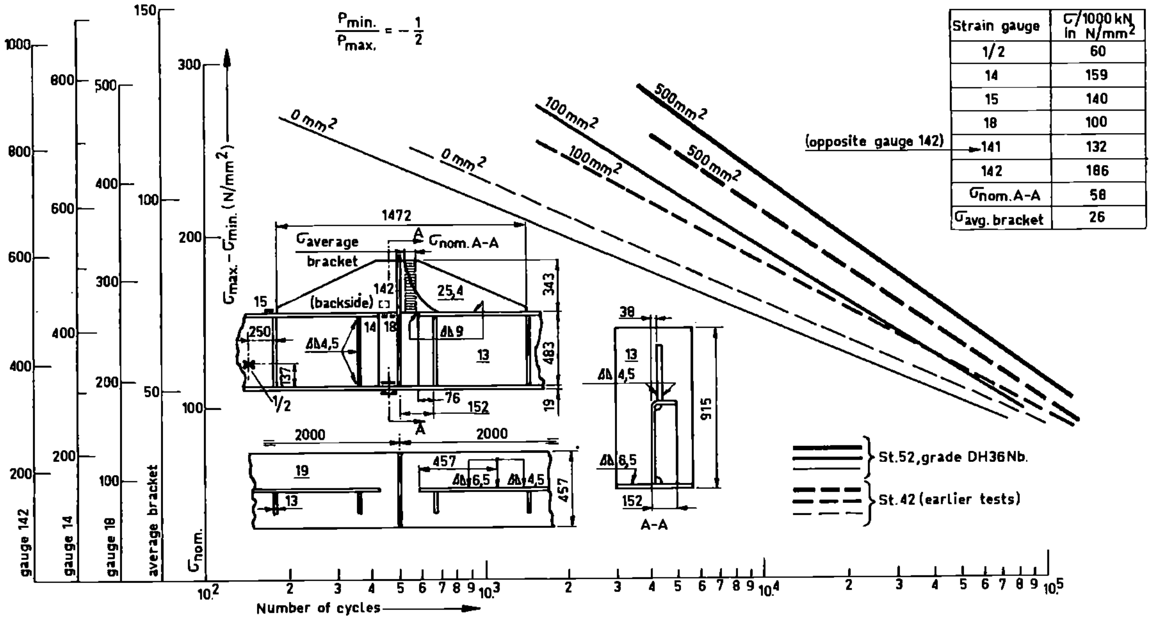
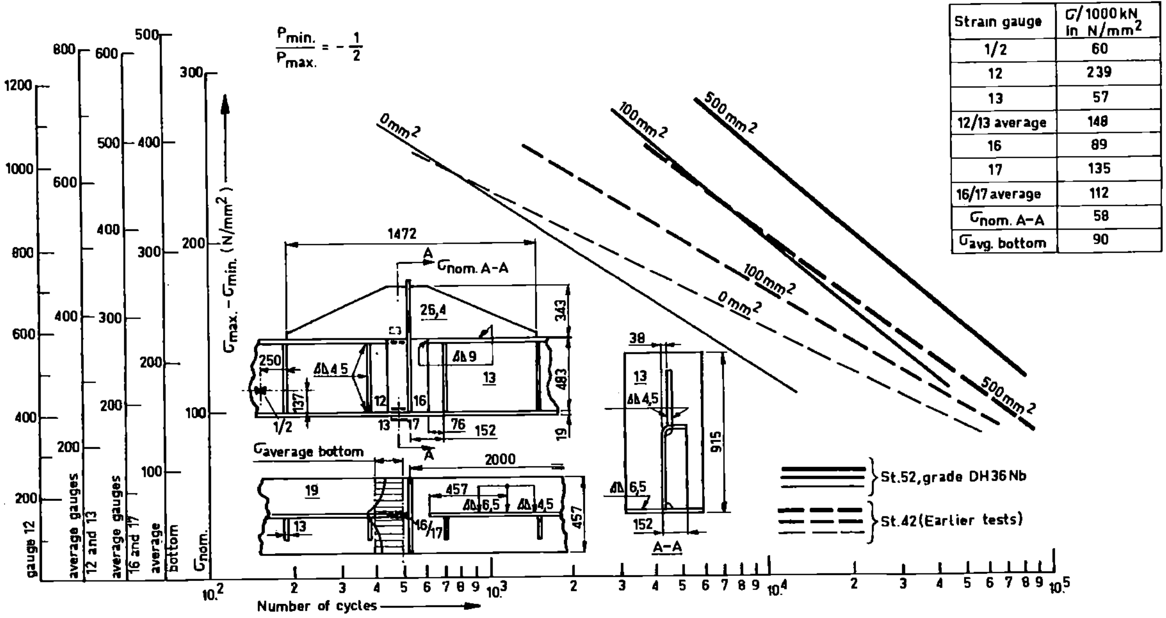


Fig. 13 Comparison of Test Data Obtained in France and Belgium for 5 mm Crack Length (a or a_{eq}); St. 42 grade D and St. 52 grade DH 36 Nb. Axial Repeated Loading (All Data corrected for Finite Width)



Strain gauge	σ/1000 kN in N/mm²
1/2	60
14	159
15	140
18	100
(opposite gauge 142) 141	132
142	186
σnom. A-A	58
σavg. bracket	26

Fig. 14 Comparison of Results for St. 42 grade D and St. 52 grade DH 36 Nb Brackets, +20°C



Strain gauge	σ/1000 kN in N/mm²
1/2	60
12	239
13	57
12/13 average	148
16	89
17	135
16/17 average	112
σnom. A-A	58
σavg. bottom	90

Fig. 15 Comparison of Results for St. 42 grade D and St. 52 grade DH 36 Nb Bottom Details, + 20°C

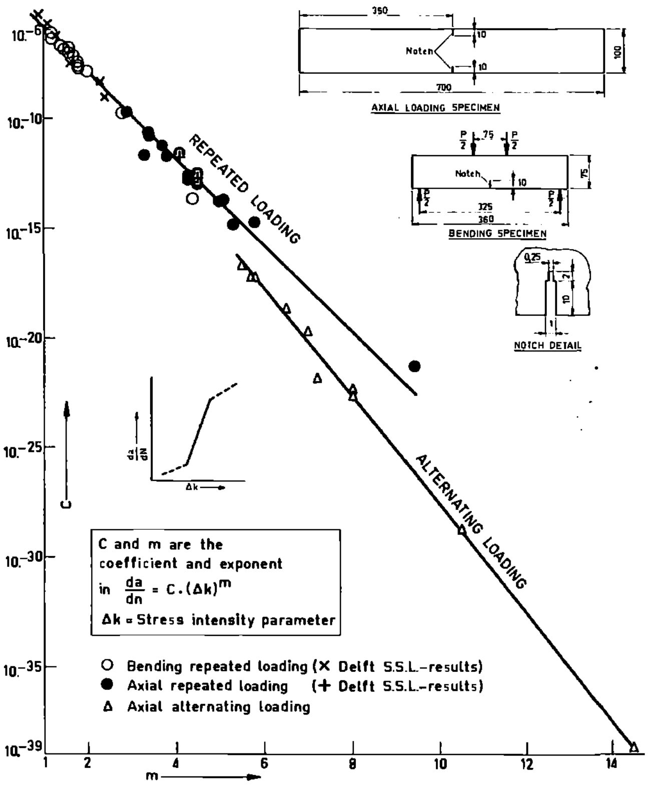


Fig. 16 Relationship Between C and m from Belgian Experiments with Two Steels, Three Plate Thicknesses and Three Types of Loading

A fourth approach in which the triangularity of the stress distribution in the brackets of the French and Dutch specimens has been taken into account, has also led to satisfactory results. For clarity the curves have not been included in the figures.

Fig. 19 gives all the notched plate data. The important, but unwelcome, fact appearing in this figure is that the groups of curves I and III do not coincide. Yet both are for repeated loading and the difference between the type of loading (bending or axial) has been accounted for by using appropriate fracture mechanics formulae. There remains the difference in the stress gradient causing unequal stress/strain histories at the crack tips. That apart, it should be observed that generally in fatigue bending the loading is 'purer' than in axial loading, where some secondary bending is often unavoidable which may be responsible for 5 to 10% higher stresses at the notches.

As a conclusion to this section the reader is asked to recall what was said in Section 2.4: Good correlations were also obtained between the results of all structural specimens by plotting these as a function of local stresses; Figs. 13, 20 and 21 illustrate this. Figs. 20 and 21 summarise all experimental results for direct use in design. The position of the curves for the structural specimens in relation to that for the unwelded notched specimens is particularly valuable, because experiments with the latter are relatively inexpensive.

6. INFLUENCE OF MEAN STRESSES

Many experts hold the opinion that for welded structures the range (or double amplitude) of cyclic loading determines the fatigue behaviour; the mean stresses are thought to be of small importance. This is related to the presence of residual stresses of yield point magnitude. The upper peak of the cyclic stress is always close to the yield point provided that the cyclic stresses are rather small. But in highly stressed structures, local yielding will cause a reduction in the magnitude of the residual stresses and the mean stress will soon become equal to zero at points of stress concentration. It may seem that for these cases mean stresses again are unimportant, but that is not correct. Severe cyclic loading combined with tensile mean stresses may cause more plastic deformation during the tensile than the compressive part of the cycle; little or no crack closure is possible when the stresses are compressive. From this it may be concluded that:

(a) Mean stresses are more important for crack propagation than for crack initiation.

(b) The adverse effect of mean stresses will not only appear in high stress loading but also in mixed loading (high and low).

(c) Steels with high yield point will suffer less from mean stresses than mild steel.

All the points are of interest for ships.

In Section 7 much attention will be devoted to the role of mean stresses in connection with non-constant amplitude loading. In the following only constant load experiments are considered.

6.1 Unwelded specimens

In Fig. 11 Wöhler's curves for 1 mm crack length show that the results for axial alternating and axial repeated loading are well 'in line' but for 20 mm crack length (Fig. 12) they lie wide apart. It is evident that from the viewpoint of crack initiation the mean stresses are insignificant. The more the cracks increase in length, however, the greater the influence of mean stress on the rate of propagation. At 5 mm crack length (figure not included) the position of the various curves is between those of Figs. 11 and 12. Fig. 10 confirms the picture. These results apply to complete fracture. Speaking in terms of cyclic stresses it can be said that +168/–168 N/mm^2 was equivalent to 195/0 N/mm^2 (N = 10^5; St. 52 DH 36).

6.2 Welded specimens

The French specimens (Fig. 13) have been subjected to cyclic loading with P min/P max = 0 and $-\frac{1}{2}$.

All data (two steels, two types of specimen, 5 and 20 mm crack length) lead to the conclusion that there is little or no influence of mean stress.

Apparently the welding stresses have great effect, so long as the cracks are within their region.

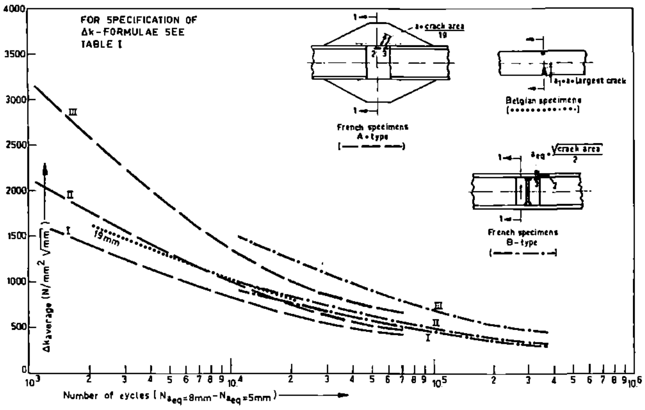


Fig. 17 Comparison of ΔK — ΔN Curves for French Specimens Type A and B and Belgian 19mm Bars St. 42 grade D. Axial Repeated Loading (Results for St. 52 are similar)

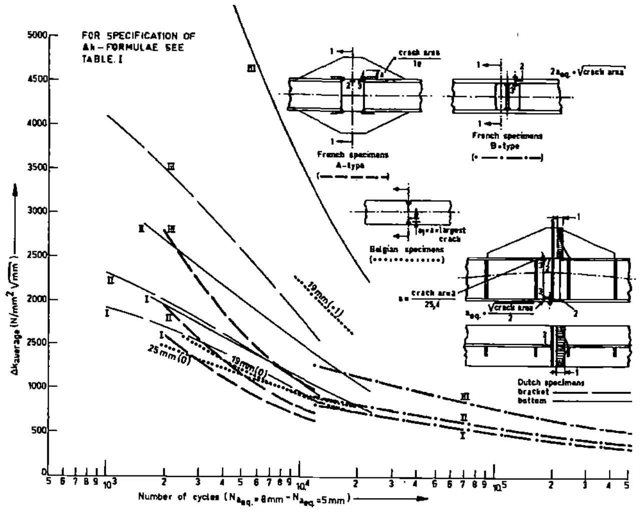


Fig. 18 Comparison of ΔK – ΔN Curves for French Specimens Type A and B, Belgian 19 and 22 mm Bars and Dutch Large Scale Specimens (Bracket and Bottom Details) St. 52 grade DH 36 Nb.
Dutch and French Specimens P min /P max = $-\frac{1}{2}$
Belgian Results P min/P max = 0 and –1 respectively

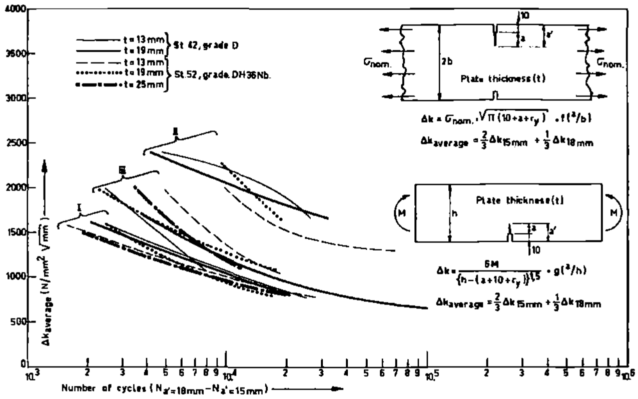


Fig. 19 ΔK – ΔN Curves for Axial Repeated Loading (I), Axial Alternating Loading (II) and Bending Repeated Loading (III). Belgian specimens

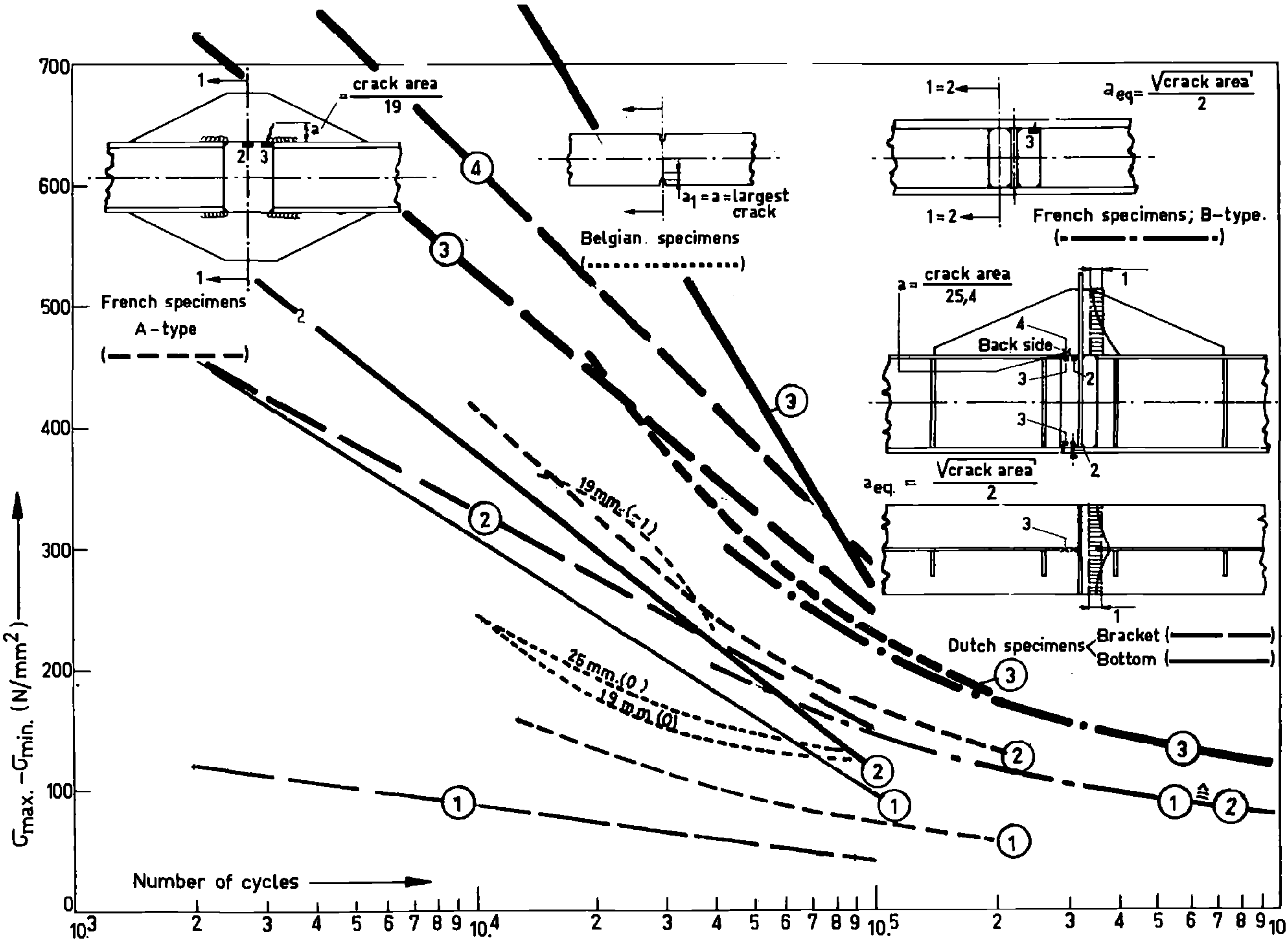


Fig. 20 Comparison of Test Data Obtained in France, Belgium and The Netherlands for 5 mm Crack Length (a or a_{eq}) St. 52 grade DH 36 Nb. Dutch and French Specimens P min/P max = $-\frac{1}{2}$, Belgian Results P min/P max = 0 and –1 respectively. French and Belgian Data Corrected for Finite Width

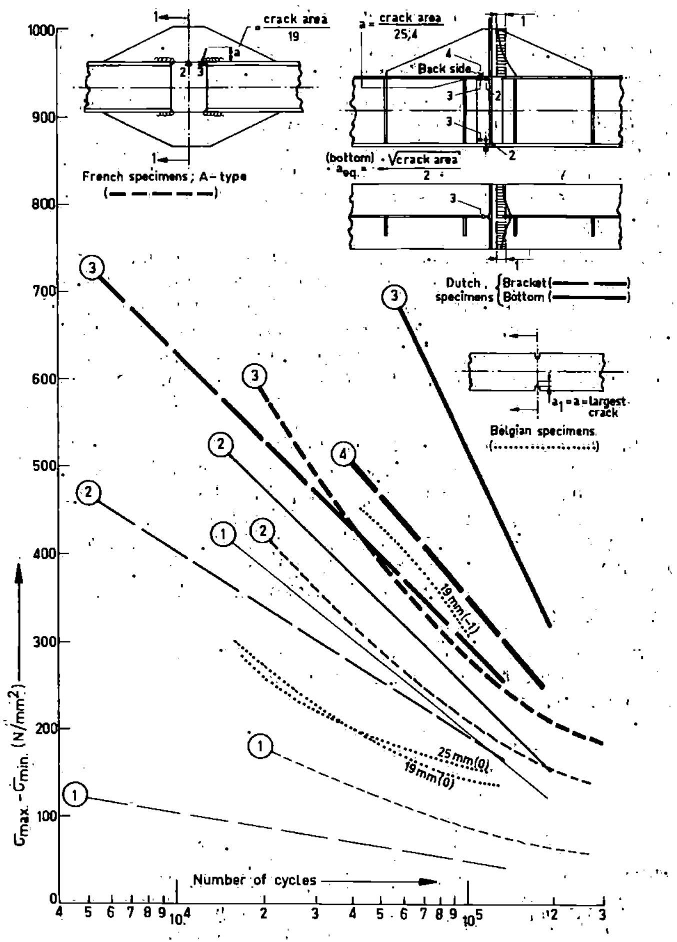


Fig. 21 Comparison of Test Data Obtained in France, Belgium and The Netherlands for 20 mm Crack Length (a or a_{eq}) St. 52 DH 36 Nb. Dutch and French Specimens P min / P max = $-\frac{1}{2}$, Belgian Results P min / P max = 0 and −1 respectively. French and Belgian Data Corrected for Finite Width

7. ESTIMATION OF THE FATIGUE LIFE OF SHIP STRUCTURES BY EXPERIMENT AND/OR CALCULATION

7.1 Ships and aircraft

The greatest need for accurate predictions of fatigue life is in aircraft design and construction. This is primarily associated with the fact that weight savings are of great importance, which has led to the use of high strength light alloys. Unfortunately these are very notch sensitive. Crack growth under cyclic loading is rapid and critical crack lengths are in the order of magnitude of only a few centimetres.

Summarising, the following differences exist between ships and aircraft in connection with fatigue:

(i) For ships, critical crack lengths are an order of magnitude greater than for aeroplanes, (see Section 2.2).

(ii) Due to this, and in view of the presence of weld defects in ships, attention should be paid mainly to crack propagation, (see Section 2.3).

(iii) Cracks in ships can easily be discovered before becoming critical which reduces the need for accurate calculations.

(iv) For aeroplanes reliable predictions with the aid of experiments (for instance flight simulation with prototypes) are required not only from a safety point of view but are also justified economically in view of the large number of aircraft of one type.

(v) Fatigue data for welded structures show more scatter than data for riveted structures, (defects, residual stresses, weld deformations, differences in composition and mechanical properties of weld, heat affected zone and parent metal). This means that predictions of crack initiation for highly stressed components such as hatch corners of 'open' ships and details of offshore structures cannot be made very accurately (Section 2.3).

(iv) The loading of ships is more complicated than that of aircraft, (see Sections 2.1 and 2.4). This is a handicap both for experiments and for calculations. (The use of strain gauges giving data about real structures under service conditions may be indispensable, see Section 2.4).

(vii) The environment of ships' structures is very corrosive, (water, air, cargo).

The foregoing points indicate why predictions of fatigue life in shipbuilding cannot be made as accurately as in aircraft building, and also why the need is not so great! This does not mean that the present situation in shipbuilding is satisfactory, as witnessed by the extensive use which is still made of the Palmgren-Miner Rule.

7.2. The Palmgren-Miner Rule and the significance of mean stresses

Important mistakes can be made when this rule is used outside the domain for which it has been found to be reasonably reliable. Sherrat [(21)] has indicated some limitations of the Miner Rule:

(i) At all stress levels, N should be between 10^4 and 10^6 cycles. Consequently very high and low stresses may not occur.

(ii) The stress cycles are well mixed.

For such cases $\sum \frac{n}{N}$ will not deviate more from 1 than 0·6 on the low and 1·4 on the high side; this is insignificant when translated into log numbers.

$$\text{For } N = 10^6 \text{ cycles}, \frac{n}{N} = 0{\cdot}6 \rightarrow n = 6 \times 10^5; \log N = 5{\cdot}8$$

$$\frac{n}{N} = 1{\cdot}4 \rightarrow n = 1{\cdot}4 \times 10^6; \log N = 6{\cdot}15$$

The difference in relation to log 10^6 is about 3% which corresponds to differences in cyclic stress amplitudes of some 5%.

Although, as will be seen, the Miner Rule is not applicable for the calculation of the whole fatigue life of ships' structures, it is certainly of value for the calculation of the fatigue damage for more or less stationary conditions, (for instance one voyage). In such cases the following observations, which are valid for the whole lifetime of a ship, do not apply:

(a) When cracks propagate the conditions at the crack tip change with crack length. Miner's Rule many only be applied for periods during which the crack factor of the stress intensity parameter K remains practically constant (for instance one year).

(b) Sequence effects are always important, but especially for the crack propagation stage. For instance residual stresses caused by high loads have considerable influence on the amount of crack closure. Furthermore small stress amplitudes have little or no effect when cracks are small, but may contribute significantly to the propagation in a later stage. (Haibach's adjustment of Miner's Rule for low stresses is an essential improvement [(37)]). It should be realised that this aspect of sequence effects is not of a random character like most load parameters.

(c) Changes of mean stress (still water stresses) cannot be taken into account in Miner's Rule. Again, the use of the rule should be restricted to stationary conditions, but now with respect to mean stress. Mostly this will mean that for each voyage $\Sigma\ N/N_i$ must be calculated.

In Section 6, it has been shown that for constant amplitude loading the influence of mean stress on crack propagation is large. The three step programme of Fig. 7 (see Section 3) led to even more remarkable results.

For mild steel gr. A: N was 4.53×10^4 (significant stress 150 N/mm^2); for DH 36: N was 2.6×10^5 (significant stress 180 N/mm^2).

When both steels are compared for a lifetime of $N = 4.53 \times 10^4$, the difference between the fatigue strength of mild steel and DH 36 is expressed by 150 N/mm^2 and 250 N/mm^2. This is much more than for constant amplitude loading.

It may be concluded that steels with high yield point behave much better than mild steel in conditions where the still water stresses differ greatly from one voyage to another.

Quite another way of looking at the results is indicated in Fig. 22. When simplifying the programme into a pure two-stage one (see Fig. 22a), thus neglecting the 50 cycles with high stresses, there are several possibilities to compare the results with those for constant loading, for instance as in Fig. 22b. The number of cycles valid for Fig. 22b can be taken from Fig. 10. It results in $N = 6 \times 10^5$ cycles for P min/P max = 0 and $\sigma_{max} = 150$ N/mm^2 (mild steel gr. A).

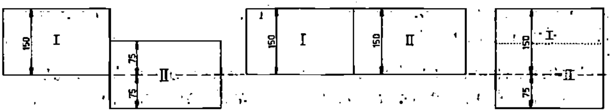


Fig. 22 Simplification of the Three-Step Programme of Fig. 7

The three-step programme for mild steel gr. A only allowed 4.53×10^4 cycles. It is clear that the increase in severity of the programme by substituting the alternating loading part for repeated loading of the same amplitude (Fig. 22b), is not sufficient to account for the regular change in still water stresses and a small number of stress cycles of larger amplitude. For DH 36 the difference between Fig. 7 and Fig. 22b is much smaller: $N = 2.6 \times 10^5$ against $N = 1.3 \times 10^5$. For mild steel Fig. 22c corresponded approximately with Fig. 7 while for DH 36, Fig. 22c was much more severe than Fig. 7.

That the changes of mean stress are mainly responsible for the foregoing surprising results may be concluded from the results of the multi-step programme with constant mean stress (Fig. 8).

For mild steel gr. A the number of cycles was $N = 5.56 \times 10^6$, for a maximum amplitude $\sigma_{max} = 240$ N/mm^2. The corresponding figures for DH 36 were 8.24×10^6 cycles for $\sigma_{max} = 290$ N/mm^2. In this case the difference between both steels is much smaller and is about equivalent to the differences found for repeated loading or for alternating loading at 10^4 load cycles.

From investigations in Darmstadt, Buxbaum(38) concluded that changes of mean stress are important when:

- their frequency of occurrence is smaller than 1/20 of that of the main cyclic stresses;
- the amplitude of the mean stresses is greater than the RMS of the amplitudes of the main cyclic stresses.

For those who still like to apply Miner's Rule for the whole lifetime of a ship the present authors suggest the use, as a simple significant stress, of the sum of the range and mean stress instead of the range only (range = double amplitude). Records of service stresses should be treated correspondingly; in that way cumulative frequency distributions of stresses represent much better the fatigue loading of a ship than is the case if stress ranges alone are used.

7.3 Procedures for predicting the fatigue life of ships

Calculations using Miner's Rule may be looked upon as a rough method for the prediction of the fatigue life of ships' structures. It is sometimes thought that a good method is the testing of real structures with service conforming loading. But as Freudenthal(39) says 'This is almost as much an over-simplification of the problem as the use of constant amplitude tests at the most damaging level of the spectrum'.

The point is that we must know how severe the loading is in connection with fatigue as compared to other possibilities. This can only be established by applying a great number of the latter in testing. Even then the information thus obtained is only really valuable when the probability of occurrence of each of the service-conforming loads used can be indicated.

Another procedure consists of a systematic analysis of the influence of all possible load parameters on the fatigue life. In the aircraft industry, many people have been working along this line for years. Yet Schijve, in an informative and comprehensive paper on cumulative damage(40) is not very optimistic, despite the valuable work carried out for instance in Darmstadt by Gassner, Haibach and co-workers(41).

In the marine field the situation is even worse, as will be clear from what has been said about the differences between aeroplanes and ships.

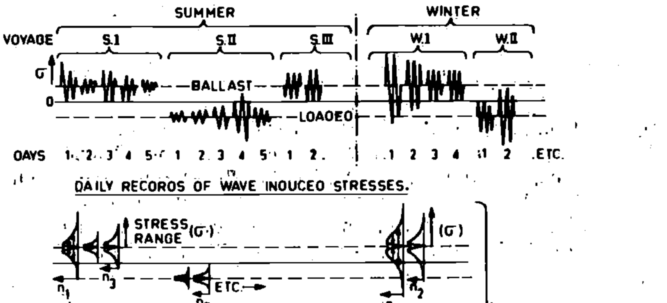


Fig. 23 Possible Simplification of Records of Wave Induced Stresses With a View to Fatigue Experiments

A third procedure which appears sophisticated and modern is random loading. Apart from other objections it must be emphasised that a ship is not a randomly loaded structure. For instance, summer and winter conditions and ballast and loaded conditions are often well defined. Of course a combination of the deterministic and random parts of the complete load spectrum would be an excellent approach (see Fig. 23), but simplifications of that procedure are thought to be justified in many cases.

A simplification which will be welcome to investigators disposing of constant amplitude fatigue testing machines is that shown in Fig. 23f and 23g. The short-term distributions (one day, one voyage) are thought to be equivalent to constant amplitude packets with a double amplitude equal to the Root Mean Square of the range-record for one day and one voyage. Such a conversion was first proposed by Paris(42). Good results have also been obtained by Swanson et al (43) but Schijve's results(44) are in disagreement.

The method will generally give over-optimistic results because the peaks of the short term distributions are suppressed. This has been confirmed by Lewszuk and White(45) who have carried out experiments with welded specimens. It seems that when Miner's Rule is used for the conversion of short-term random loads into constant amplitude loads (with the same number of cycles), experimental and calculated results will agree better.

A method in which the effect of the peaks is maintained to a certain extent is illustrated in Fig. 23d and e. A triangular frequency distribution of which the maximum value is equal to the RMS of the ranges times $\sqrt{3}$, has the same RMS value as the original short-term record. RMS $\sqrt{3}$ is equal to the average of the 'one tenth highest values' of the short-term record; consequently the peaks are well taken into account.

Fig. 23 has been included for various reasons:

(i) It gives some feeling for the advantages and shortcomings of the various procedures.

(ii) It may be seen as a realistic research programme for the study of cumulative damage for shipbuilding.

(iii) The various procedures might be accepted as standard or as a means of reference for comparing the fatigue performance of ship structures. There is a great need for standards, because the results of too many alternative procedures are difficult to compare and may give rise to much confusion.

It is thought that the procedures of Fig. 23 are definitely more reliable for prediction purposes than the results of constant amplitude loading evaluated using Miner's Rule.

(iv) For each type of testing equipment an optimum procedure can be chosen.

8. CONCLUSIONS

(i) The 'fail-safe' concept applies to most ship structures (cracks allowed). Only for critical details, which are small in number, is a 'safe-life' approach justified (prevention of crack initiation).

(ii) The propagation stage of crack development is of primary importance for ships because at weld defects crack initiation takes relatively little time.

(iii) Frequency distributions of stress amplitudes are of limited value for predictions of fatigue life. Mean stresses are also important. (Range + mean stress may be a satisfactory representative fatigue stress).

(iv) The foregoing is related to the experimental result that mean stresses have great influence on the rate of crack propagation.

(v) By applying strain gauges close to possible crack initiation points in ships, difficulties in connection with complicated loading conditions (phase, type) and structural configurations will be greatly reduced. The output of the strain gauges can be used with some confidence either for establishing the loading for fatigue experiments or for calculations of fatigue life.

(vi) A linear relation has been observed between m and log C of the Paris-Erdogan crack propagation law.

(vii) In constant amplitude loading the difference between the fatigue strengths of a higher strength steel and mild steel was small (a maximum of 15%). However, programmed load experiments with various mean stresses showed a large advantage in favour of higher strength steel. This conclusion is only valid for 'fail-safe' design, because it is based on crack propagation experiments.

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DISCUSSION

Mr K. V. Taylor, B.Sc. (Eng) (Fellow): The authors have produced an interesting paper full of valuable subject matter but also containing a number of pertinent statements which could have a considerable bearing on the techniques used in ship structure design procedures involving fatigue and fracture mechanics. The following three main points stand out: (i) the importance in the order of stress reversals of different magnitudes; (ii) the importance of mean stress on fatigue life; (iii) the lack of confidence in Miner's Rule for general application.

In the design stage, loadings, in terms of stress reversals, can be predicted analytically by probabilistic techniques to give data related to their frequency of occurrence in the service life of the structure. There is no one set pattern of stress. However, what one should attempt to simulate in the fatigue testing is a typical average pattern and investigators should try to copy with random load machines this 'average' behaviour. While agreeing with the authors that consecutive stress reversals cannot be selected on a completely random basis, the cumulative frequency diagram nevertheless provides information on the numbers of stress reversals for different stress levels to make up a test sample. From this information and the still water stress pattern it should be feasible to derive a year's loading pattern which could be regarded as 'standard'. At the same time the pattern ought to be capable of changes to allow for higher wave induced stress levels and different still water stress behaviour so as to take account of any influence these effects could have on fatigue life.

The view held recently that with welded structures the range of cyclic loading determined the fatigue behaviour, and that mean stress was of little importance, has presented the designer with an easier problem to solve, but now the authors have very firmly thrown these ideas back into the melting pot. As pointed out earlier, still water stress for a large number of ships will vary in a random manner considerably more than that shown in Fig. 23. It is therefore going to be far more difficult to take a random mean stress into account both experimentally and analytically.

The third point concerns the lack of confidence in Miner's Rule for general application. This method has been one of the main building bricks for fatigue design techniques and, for all its limitations, it has been the only simple method available by which fatigue damage can be assessed. The constraints as given in Section 7.2 will have a marked influence on its use for general fatigue behaviour where conditions relating to (i), (ii), (a), (b) and (c) cannot be met.

Finally, in the authors' conclusions the use of strain gauges is advocated close to possible crack initiation points in ships, and while such a procedure has been used by Lloyd's Register to investigate the structural behaviour of a typical bulkhead and inner bottom plating joint in a bulk carrier, it cannot be considered a viable procedure unless for the purpose of obtaining data on typical service behaviour. In this instance, however, crack growth was involved necessitating a realistic service stress spectrum to be determined for the region in question and the data were used in association with one of the Society's crack propagation programs based on the Paris-Erdogan law.

Ir W. Spuyman (Fellow): The authors have really succeeded in squeezing as much information on fatigue strength as possible into the few pages that our Secretary allowed. Nevertheless I think that a handy and complete reference work has been produced in which, guided by the authors, a modern and practical insight can be obtained into a fail-safe fatigue life of present and future marine structures. General developments are such that it may be expected that fatigue strength will be one of the main deciding parameters for structural reliability.

The fail-safe concept, although not always readily accepted in words, is usually plainly accepted by deeds, as long as watertightness and other critical service functions are not endangered. That there are still questions left may not be the authors' fault, and possibly one still needs some guidance in these matters. It will be much appreciated if the required guidance can be given on the following questions.

With a view to developments into still larger, lightweight, low production cost marine structures which might also operate in regions with dominating very low temperatures, even relatively small fatigue cracks of lengths in the order of plate thickness (as in Section 2.2) might be dangerous from the brittle fracture point of view. I failed to notice this temperature influence in the Wöhler curves that might serve as a starting point for the prediction of a fail-safe fatigue life. Where these service conditions might easily occur, it would be much appreciated if the authors could give an indication of the extent to which the Wöhler curves would be adversely influenced by very low temperatures.

Further, weld defects and in my opinion also bad flame cut edges in the heat affected zone may also be important sources for a crack to develop. Could some idea be given about the quality of flame cut edges to be obtained in order to be safe from the fatigue point of view, because this could be important, bearing in mind the low cost production philosophy?

My last remark concerns Fig. 23. Given the considerable importance of the state and frequency of change of the mean stress on crack propagation as explained in Section 7.2, one fails to see the use of the possibly simplified loading given in Fig. 23g. In my understanding, this type of loading is not useful from a marine structures fatigue strength point of view, and is the one fatigue researchers are most unhappy with. Would the authors please explain this?

I should like to conclude my remarks by expressing the sincere hope that the authors may be given the opportunity to obtain the vitally needed realistic service stress/strain histories of the nature given in Fig. 23a.

Professor E. V. Lewis M.S. (Fellow) (read by the Secretary): In an earlier paper, the first author stated, 'It is a favourable circumstance that fatigue cracks propagate very slowly in ships' structures'[48]. Hence, the safety of the ship is seldom threatened by fatigue. This is a fortunate circumstance, but it is an unstated assumption of the present paper that the cost of repair of fairly frequent nuisance fatigue cracks is a significant figure in ship operation—especially when the cost of ship time out of service is included. Consequently, as ship structural techniques and design standards are refined, the subject of fatigue becomes increasingly important.

A noteworthy feature of this paper is its emphasis on the differences in the fatigue loading of ships as compared to other structures. Not only are the loads reversed and irregular in magnitude, but there is a constant shift of mean value (still water bending moment). This is particularly well demonstrated by Fig. 23. The authors give some interesting suggestions as to how such complex loadings can be approximated in standard laboratory experiments on structural details.

The paper is of value also in presenting some highlights of the extensive international experimental research programmes in Europe. The authors offer convincing arguments that research can be concentrated on the propagation problem, since many undetected cracks probably exist in every ship's structure. Further experimental results will be awaited with interest.

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Professor G. Aertssen (Fellow): When weight reductions were allowed by classification societies on container ships, where higher strength steels were used, some doubts arose concerning the problem of fatigue cracking. Was fatigue strength not better indeed for this steel than for mild steel as put forward in some quarters? That the ship research centres of France, Germany, Holland and Belgium undertook a co-operative investigation trying to solve the problem, with the financial support of the CECA, was meritorious to the profession. Professor Nibbering is to be congratulated not only on having accepted the responsibility for the co-ordination of the tremendous experimental work, but on giving here, with Mr Scholte, a comprehensive survey of the results.

The survey is divided into two parts. Focussing attention first on the part where differences are sought only in the fatigue strength of mild steel and higher strength steel, it is somewhat disappointing that the data of various laboratories are not in line, but the overall conclusion of the authors that a 10 to 15% advantage is obtained by using steel 52 DH instead of mild steel 42 A may be corroborated by the performance data of two Belgian ships, the ore carrier MINERAL SERAING, deck in steel 42, and the container ship DART EUROPE, deck in steel 52. This 10 to 15% advantage is best emphasised by the German data obtained on centrally notched plates shown in Fig. 10, and an endeavour is made to enter the data of the ore carrier and the container ship in this Fig. 10.

Both ships have the same length, 218 m, but the open container ship DART EUROPE has a deck inertia modulus of $16{\cdot}4 m^3$ against $25{\cdot}8 m^3$ for the MINERAL SERAING. Fortunately, the container ship is much finer, block-coefficient 0·60 against 0·82 for the ore carrier. Therefore, the wave bending moment is much smaller for the container ship, with the result that the wave stresses are nearly the same for both ships. However, due to the higher speed in waves the container ship sustained higher whipping stresses than the ore carrier. Moreover, the container ship is in a strong

TABLE II Longitudinal Deck Stresses in a Sea State Beaufort 10

Ship's Name	Condition in Waves	Wave Kg/mm^2	Whipping Kg/mm^2	Still Kg/mm^2	Total Kg/mm^2	$\frac{P_{min}}{P_{max}}$	Range Kg/mm^2	Mean Kg/mm^2	RMS Kg/mm^2
Ore	Loaded hogging	3·0	1·1	–4·2	–0·1	0	12·3	–6·2	3·0
Carrier	Loaded sagging	–5·0	–3·0	–4·2	–12·2	0	12·3	–6·2	3·0
MINERAL	Ballast hogging	2·8	1·1	2·7	6·6	–1	11·6	0·8	3·0
SERAING	Ballast sagging	–4·7	–3·0	2·7	–5·0	–1	11·6	0·8	3·0
Container	26 ft hogging	2·6	2·4	11·0	16·0	0	16·2	8·1	4·0
ship	26 ft sagging	–4·4	–6·4	11·0	0·2	0	16·2	8·1	4·0
DART	30 ft hogging	2·6	2·4	6·0	11·0	–1/2	15·8	3·1	4·0
EUROPE	30 ft sagging	–4·4	–6·4	6·0	–4·8	–1/2	15·8	3·1	4·0

hogging condition which gives higher still water stresses than the ore carrier.

It is not difficult to ascertain the three components of the longitudinal deck stresses, wave stresses, whipping stresses and still water stresses of the ore carrier in both conditions, ballast and loaded, and they are given for Beaufort 10 in Table II, together with the same components for the container ship, where two extreme load conditions are considered on the Atlantic, westbound at 26 ft draught and eastbound at 30 ft draught. A factor of 37·5% is applied to the significant wave stress and to the whipping stress range to obtain the hogging part, whereas a factor of 62·5% gives the sagging part of the low cycle wave stresses. However, the full range of the whipping stresses is accounted for when ascertaining the sagging part of the slam. This may be surprising but the authors did well when in Fig. 2 they emphasised the important effect of slamming on the total stress.

Taking the container ship at 26 ft draught, ignoring the whipping stresses gives deck stresses of 13·6 Kg/mm^2 in hogging and 6·6 Kg/mm^2 in sagging condition, both tensile stresses, thus a stress range of 7·0 Kg/mm^2, which is half the stress range 16·2 Kg/mm^2 when whipping stresses are accounted for. The mean values of the whipping stresses at sea are related to the selected sea state, a widespread Beaufort 10, whereas mean values are chosen for the still water stresses in both directions. For both ships the components are calculated indeed in a large spreaded sea state Beaufort 10, it being assumed that the frequency of occurrence of higher waves is rather small and that fatigue in these exceptional sea states is not so much a matter of concern, and further that stresses induced in more moderate seas are so small that no harm is expected from them.

Although the ore carrier sailed on various routes, for comparison the same route is chosen as for the container ship. The number of cycles in 20 years is 2·5 × 10^4 for the Atlantic westbound and 2·5 × 10^4 for the Atlantic eastbound. It is remarkable that the ranges of the loads for each direction are approximately proportional to the yield strength of the steel used. They justify the varying load tests programmed by the authors. The mean stresses are given for each load condition and the changes of these mean stresses are important because, as mentioned by Buxbaum, (a) their frequency of occurrence is smaller that 1/20 of that of the main cyclic stresses, and (b) the amplitude of the mean stresses is greater than the RMS of the main cyclic stresses. The RMS, corrected for whipping stresses, is given in the last column of Table II.

As suggested by the authors, the 10 to 15% advantage for higher strength steel deduced from constant amplitude tests is probably surpassed due to the changes of mean stresses as shown by the varying-load tests.

The table is supposed to be no more than a first approach to an analysis of the successive loads at sea on these two ships, and it is expected that the large amount of data available may encourage the authors to extend their work on a further investigation of actual ship's data.

It should be added that neither the ore carrier, which is ten years old, nor the container ship, which is five years old, apparently suffer from fatigue.

Mr P. R. Christopher, B.Sc. (Member): It is obvious from the controversial statements which occur in this paper in relation to the influence of increased strength and of mean stress, that all is far from being understood. This applies to the propagation of cracks in both small and large specimens. There is clearly some ambiguity as to how to apply cumulative loading and what effect it has. It is said that random loading is a good thing because it produces cracks where otherwise one would not expect to find them, but it may be difficult to do this with large specimens. There is the influence of corrosion which gives rise to the possible effects of blunting cracks and the adverse effects of corrosion fatigue activity.

Professor Nibbering makes the usual assumption these days that all attention should be focussed on crack propagation, and this is taken forward in his experiments. Initiation, he says, may not take long at all in way of sharp defects. However, the fact is that this may be appreciable in many instances, and one has to remember that propagation can be much influenced by changes in mean stress. A drop in mean stress at constant stress intensity range can cause a delay to crack propagation.

I admire the scale and detail of this co-operative programme that is taking place on various types of structural connections. It shows a determination to get much information experimentally and theoretically. I note the part that is being played both by universities and by technical institutions. One wonders why in this country we have not a similar programme or have not participated in the present one. A comprehensive programme has, in fact, been set up in relation to offshore applications by the Department of Energy.

Important issues, which underlie the statements made in this paper with respect to the values of 'm' (very high in the case of the Belgian repeated axial loading experiments), are the effects of mean stress and whether or not crack closure occurs, the yield stress and cumulative damage on the mode of fracture and the way in which this is influenced in different types of steels. If the mode of fracture, which could imply ductile areas or striations and brittle elements, is important then it is clear that the conclusions the authors are trying to draw might be cast in a more general and, perhaps, meaningful light. Certainly one might suspect, for instance, that higher yield stress is less sensitive to mean stress effects at any life to failure in all cases.

The authors have considered fracture mechanics in relation to small and large specimens and have a good deal of data.

I should like to ask to what extent they have been able to relate them all bearing in mind conclusion (v). If fatigue cracks do occur in ships it might be worth while considering how the actual vessels might be used as fatigue experiments since they clearly apply the right sort of programmed loading with regard to amplitude and time. This could be done by monitoring actual cracks, in fail safe situations, or by perhaps erecting ancillary structures on the ships which could follow the strains in the seaway. I was impressed by Professor Nibbering's calculations on the various effects of growth in relation to Miner's Rule. We seem to be more certain as to what is conservative, but in some cases this could be restrictive.

I think it is time that we had a paper, perhaps before this Institution, summarising exactly what evidence we have on fatigue cracks in ships. I suspect, from what Professor Nibbering has told us, that there is evidence, not generally known, which ought to be published. There is much evidence published with respect to brittle fracture and there are even instructions as to what to do when seafaring men find a brittle crack.

I was intrigued by one statement in the paper which I think deserves more explanation. In Section 2.2 it is stated: 'It may be concluded that for modern ships, made of excellent fine grain steels, small cracks are often more dangerous than long ones'. I imagine that the authors might wish to amplify this apparent anomaly.

Professor E. V. Telfer, Ph.D., D.Sc. (Fellow): The excellent and extensive list of references appended to the authors' paper can be historically improved by the addition of a reference to Thearle's (1913) and to Haigh's (1939) Institution papers. Both can rightly be regarded as pioneering efforts and as demonstrating how long the subject of fatigue has been at least a matter of awareness in the shipbuilding industry.

In presenting his paper Professor Nibbering made an interesting allusion to Mr Ross Belch's paper at these Spring Meetings and particularly to Mr Belch's use of a welded overlap construction in the transverses, as shown in the latter's Fig. 5. Professor Nibbering regarded this overlap, as being essentially equivalent to a welded crack design and presumably, therefore, not entirely acceptable? If my interpretation of Professor Nibbering's remark is correct then I am not sure that I necessarily agree with him. For example, I am sure that not all cracks, designed or accidental, are inevitably dangerous. Consider in this connection the case of a butt-welded sheer strake. If X-ray analysis shows the presence of cracks disposed along the butt, service stressing will open out the cracks and lead to the rapid destruction of the joint. On the other hand if the cracks were disposed across the weld, or in the limit the joint was closely tack-welded, there could be no serious crack-spread which service stressing could precipitate. To return to the riveted alternative, surely the space between rivets is, in welded parlance, a crack, but to condemn rivetings on this account would hardly receive much practical endorsement!

That cracks can have many 'built-in' causes was brought home to me many years ago when I was watching a hatch side girder being flanged in the hydraulic press. I got the impression that the plater doing the work was somewhat loath to continue as long as I was watching. However, once the flanging had reached to an angle of about 40°, the plater then proceeded to file away the outer corner of the plate in way of the flange radius at each end of the plate, finally producing well-rounded outer corners. The flanging was then completed and was an excellent job.

This example certainly taught me that all sharp corners subject to high stress magnification, such as slotting through transverses for the passage of longitudinals, could have this stress magnification greatly reduced by filing away the sharp corners where this magnification is greatest and from which corner cracks invariably emanate. As a corollary to this it follows that when structural test-pieces are being prepared for fatigue testing all sharp corners should be sensibly removed before any testing starts. The neglect of this precaution could easily falsify the lessons of the whole test.

To conclude, I trust that Professor Nibbering will find my remarks not too irrelevant. I believe that successful riveting practice has much to pass on to modern welding practice and design. In particular, where a welded detail has persistently failed, it is always useful to examine why its riveted predecessor could even have proved successful.

Professor E. R. Steneroth (Member): From earlier discussions between Professor Nibbering and myself, I know that we have different opinions about the importance of crack initiation and propagation. I feel it is very important to know that crack propagation is not dangerous, but what we would now like to see are structures which give no initiation of cracks. For example, Figs. 10 and 11 in my opinion show a propagation situation because the defects which they have should not exist. Of course, we have always to realise the possibility of their existence, but what we do in real ship structures is to look, as much as possible, for any defects in the structure at stress concentrations where one might get the stress amplitudes which exist in the Figures. Those are not representative for nominal stress figures in the main hull girders.

About eight years ago I presented some views about the situation in respect of fatigue cracks. This was the result of several years' discussions with the late Mr Murray. If it were possible to decide the curves for real full-scale ship structures with their detailed design and workmanship, I think that, based upon aircraft engineering investigations, it would be possible to get figures such as I presented in that paper. These indicate that for longer lives there is about the same endurance strength for high tensile and mild steel, but at shorter lives a clear difference should be found because of the much higher yield point for the high tensile steel. Considering then the long-term distribution of stresses one must necessarily, in my opinion, expect a better fatigue life for the high tensile structure. How much we do not know, but I think it is impossible to avoid this conclusion.

It is stated in the paper that the material is damaged in front of the crack and therefore there will be a faster crack propagation the longer the initiation time. I do not agree, because we are talking about nominal stresses; if we were talking about microscopic local stresses, it might be otherwise. I do not see that one should expect a faster rate of crack propagation in the two different cases, short or long initiation time, if the nominal stresses are the same.

The Chairman (Dr A. J. Johnson): In passing I could not help noting in Section 2.1 the reference to a paper in our past Transactions in which it was argued that in the OCEAN VULCAN there were no fatigue cracks. Having been associated closely with the structural investigations on this ship it is my firm recollection that significant fatigue cracks were observed around certain discontinuities and I am sure that the records will confirm this.

The comments regarding the serious limitations on the applicability of the Palmgren-Miner Rule are of considerable importance and the authors have put this into perspective. I would be interested to know whether some of the conclusions in the paper would be equally applicable to some of the less redundant offshore structures we have having to deal with these days.

Having said that, I am sure that Professor Nibbering and Mr Scholte must have been very well satisfied with the interest the paper has generated, as must also the Institution. Obviously we shall be getting more written contributions. I ask you to express your thanks to the authors.

The vote of thanks to the authors proposed by the Chairman was carried with acclamation.

WRITTEN DISCUSSION

Professor Dr S. Marsich (Fellow): The results of tests carried out in Italy and Belgium on specimens under bending load will be reported in detail by Professor Nibbering, as indicated in the Introduction. However, it would be interesting to anticipate part of the results obtained in Italy to show both the equipment employed and the criteria used to define the numbers of cycles at which cracking commenced.

The test specimens, of which there were seven, were as shown in Fig. 24. Three were of Italian construction, made of HTS steel, and the other four were of Dutch construction. The steel of the latter four, of Belgian production, was St. 52 grade DH 36 Nb.

The first three Italian specimens were submitted to a simple alternating bending moment between +150 and −85 N/mm^2, but because of cracking in the welded seams, it was not possible to make use of the results of these tests. In order to obviate this, 12 new specimens were manufactured; the collaboration of the authors was kindly promised and will be required as soon as these tests begin.

The four specimens of Dutch construction were submitted to a programmed bending moment according to the scheme shown in Fig. 7 with the difference that the values 90 and 180 were increased to 100 and 200 N/mm^2. The numbers of cycles at which cracks started are shown in Fig. 25. The detection of a crack in the early stages of development has been made possible with the aid of electrical strain gauges.

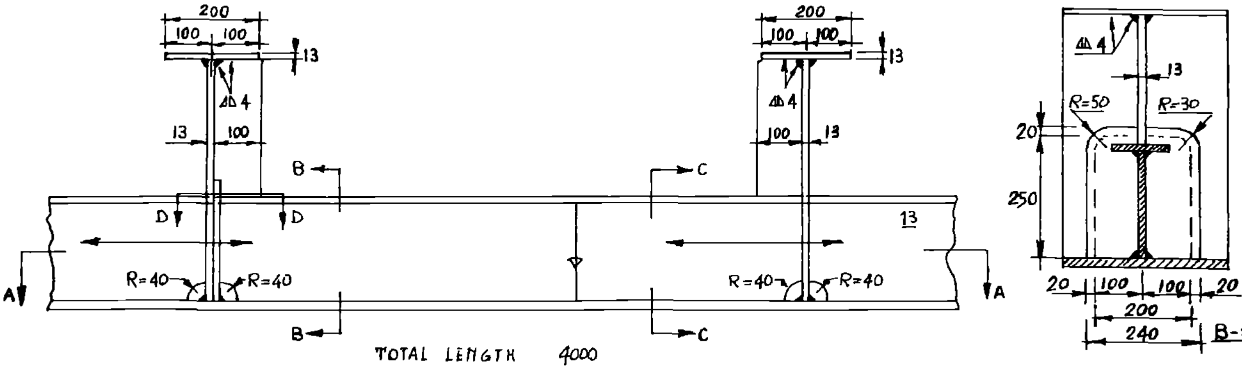

Fig. 24

The relevant strains were read at regular intervals during the specimen life and measured strain values were taped by means of an HP 2115 B computer.

As an example, Fig. 26 shows the decrease of maximum strain measured by strain gauge No. 31 of model 5 as the number of cycles increased. It clearly shows the decrease of strain starting from 0·71 × N_R cycles, N_R being the number of cycles at which the test was stopped. It was therefore possible to show in Fig. 27 the growth of the length of the crack starting from 0·71 × N_R cycles—point A—as obtained from Fig. 26. Finally, Fig. 28 shows the output of a strain gauge during one load cycle at different numbers of cycles.

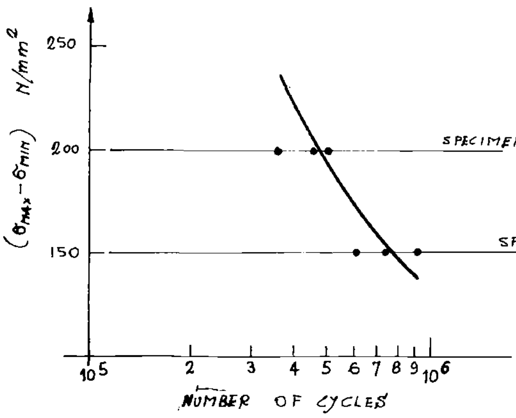

Fig. 25

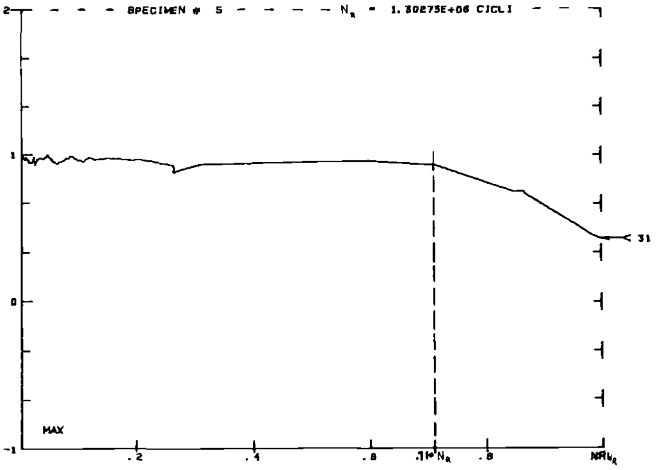

Fig. 26

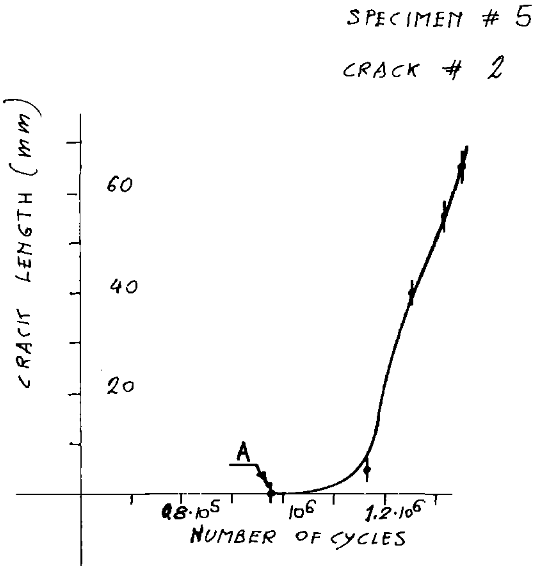

Fig. 27

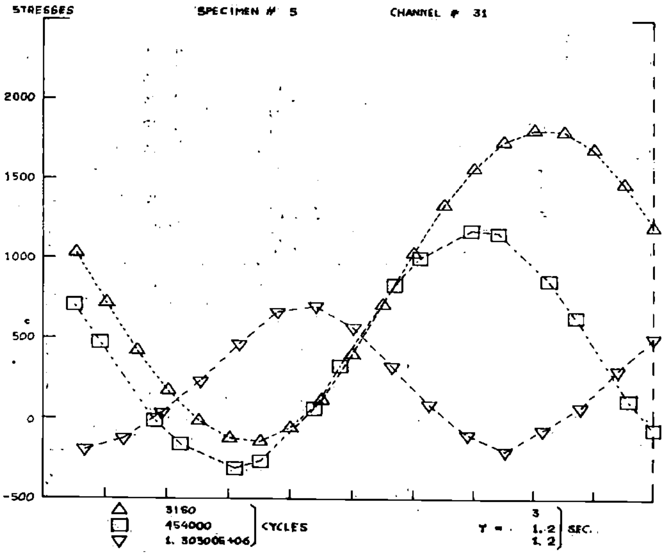

Fig. 28

Professor H. Petershagen and Dipl Ing H. Paetzold: In addition to the German tests mentioned in the paper, crack propagation measurements have been performed with specimens as shown in Fig. 10. For this purpose a measuring device was developed: Crack propagation is measured by means of an electro-magnetic sensor, following the crack tip automatically. Presently single level fatigue tests can be recorded, application in multiple level fatigue tests is planned. Evaluation of single level fatigue tests according to the Δk-concept with P min/P max = 0 and P min/P max = −1 showed different m-values. For the HTS steel DH 36 Nb, a linear relation between log da/dn and log Δk was found for Δk ≤ 1800 N mm$^{-3/2}$.

In Section 5 the authors state that m is not constant over the whole crack propagation period. In the high range of Δk-values this is due to the fact that the plastic zone at the crack tip is no longer small against the crack length. In the tests with HTS steel DH 36 Nb, this is apparently the case with Δk-values beyond the a.m. limit of 1800 N mm$^{-3/2}$. The log C/m-values obtained fitted quite well with those of Fig. 16. The line for P min/P max = −1 given in Fig. 16 was also confirmed by other data from the literature.

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49. Hanel, J. J.: 'Schwingfestigkeit und Rißfortschreitung von eigenspannungsbehafteten Rißstäben aus St 52 unter Einstufenbelastung'. Institut für Statik und Stahlbau der TH Darmstadt Heft 19, 1972.

Mr M. D. Hure: This paper gives a very detailed and accurate analysis of a large series of fatigue investigations and the authors have made a very good attempt to present these new data in a simple form directly available for the estimation of the fatigue life of hull structures. However, it must be remarked that the general result is to present an intricate and involved summary of these new fatigue data.

Within Bureau Veritas, extensive interest and study does proceed on fatigue analyses and prediction. Presently we use a very simplified method of fatigue life prediction which involves the adoption of ASME Codes covering nuclear pressure vessels—these data being concerned more with crack initiation under constant strain loading conditions, but also including the effect of maximum mean stresses. Normally, these ASME data are applied with reduction factors arising from either strain gauge measurements or fatigue results from ships in service. It is then usual for the safe fatigue life (until crack initiation) to be established, according to the Palmgren-Miner Rule.

Application of the above procedure has given good correlation with fatigue failures from ships in service and it is noteworthy that this approach does result in a variable safety factor with respect to crack initiation and at the same time, this method remains acceptable in line with current ideas of crack propagation (up to crack lengths of one metre).

It is our opinion that the acceptability of the present Bureau Veritas approach has a foundation in the following points:

(i) Fatigue acceleration due to corrosion or the cumulative effect of random stresses in excess of the Palmgren-Miner Rule are taken into consideration.

(ii) We have obtained a better parallelism between crack initiation curves and crack propagation curves in association with constant strain loadings (it is to be remembered that local cracking does not, in general, affect the overall constant strain loading within the system).

(iii) Our method seems to display very clearly the relatively rapid crack growth which can result from a few severe weather voyages.

However, and in company with the authors, we are left with two major unknown quantities associated with fatigue analysis in service, and these are:

(a) the measurement of the sea-states actually encountered by the ship during her life-time.

(b) the local stress intensification factors.

With regard to service sea-state definitions, since 1972 Bureau Veritas has instigated a programme of automatic motion measurements in association with a statistical stress counter, this data collection system being operated on several ships on a real time basis. Analysis of this programme is proceeding and the Society is readily accumulating fatigue service experience on classed ships.

With regard to local stress intensification factors, it is undoubtedly the case that the constant amplitude loading tests, as suggested by Professor Nibbering and Mr Scholte, will result in a large extension of existing knowledge concerning the intricacies of fatigue in ships. The authors are to be congratulated on this valuable paper.

Ir F. X. P. Soejadi: Particularly as a member of the ISSC Committee on Design Loads, I take a great interest in this timely paper. My special attention was drawn to Section 7.3, where the authors state 'apart from other objections it must be emphasised that a ship is not a randomly loaded structure'. I would appreciate the authors' specification regarding the 'other objections' as well as concerning 'what has been emphasised'.

The still water stress can be considered as a non-random load, but taking it as having a constant magnitude during one voyage (as in the proposed procedures —Fig. 23) is a simplification which is too general in my opinion, especially in the light of the first author's very own views that, in order to obtain the correct loading line (Fig. 11), every factor which may affect enlargements of peak-to-trough values must be accounted for(11); a shift of the still water stress level is one of these factors. Because of the low frequency of the enlargements by a variation of the still water stress level, the long-term loading line will hardly be affected, but each occurrence will affect the magnitude of the (short-term) RMS value. This is relevant since the proposed procedures make use of RMS values.

As an illustration of a possible variation of the still water stress level one of the figures concerned(50) is given as Fig. 29. Of course one cannot generalise on the grounds of this particular example; therefore a statistical study of the trend of the still water stresses may be advisable, such as was done by Ivanov and Madjarov(51).

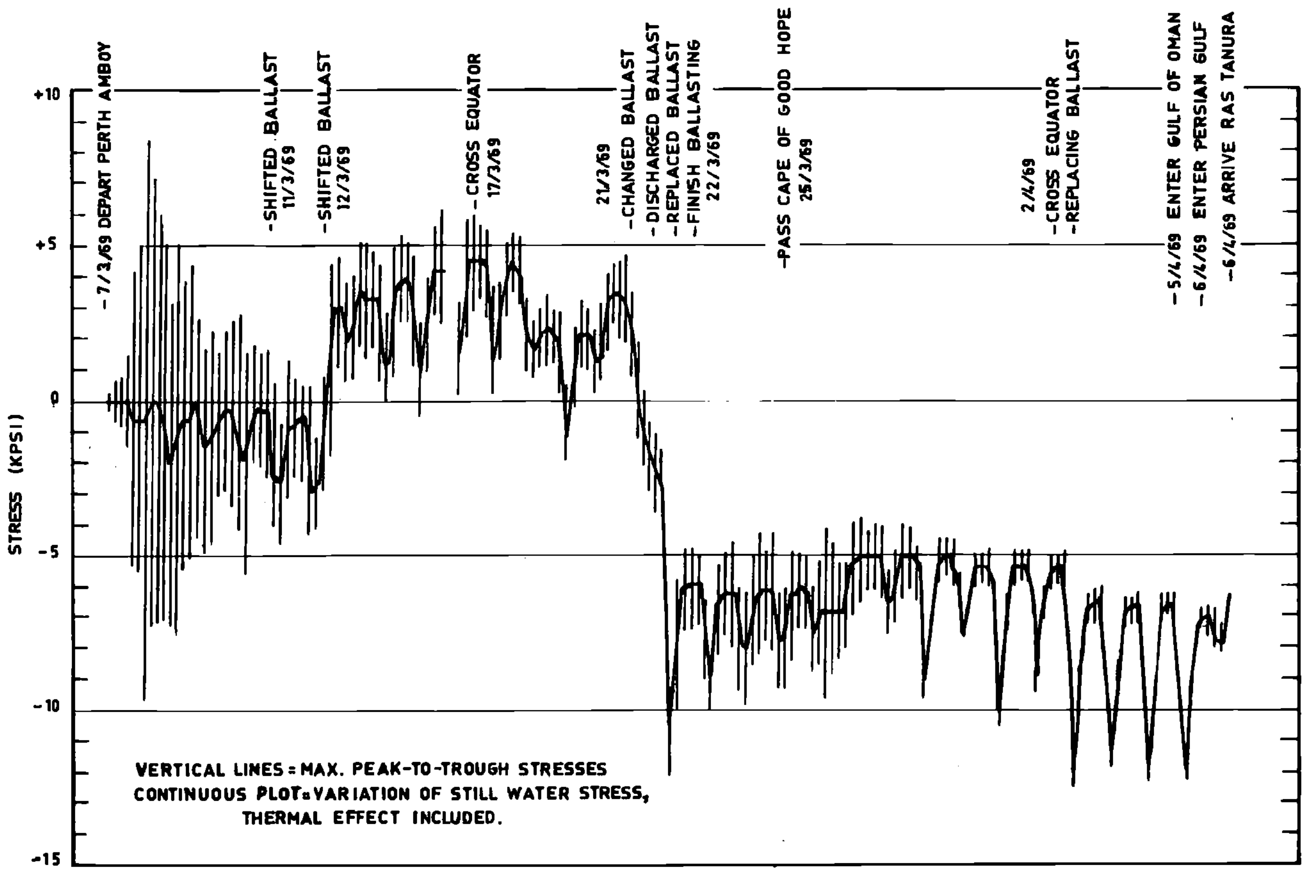

Fig. 29. Typical Voyage Variation of Midship Vertical Bending Stress, ss R. G. FOLLIS

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Mr A. T. Ractliffe, M. A., Ph.D. (Member): The establishment of design guidelines for fatigue is bedevilled not only by the large number of factors which are relevant, but also by the variability of experimental data. This may arise both from scatter in the results from one type of machine and specimen, and also variations arising from the use of different machines in different research institutions. The significance of fatigue data can therefore only be analysed on a statistical basis and the results assessed at specified confidence levels, employing information drawn from all available sources. I question the possibility of drawing significant conclusions from the authors' results without further information on their statistical variance. The lack of significant correlation between fatigue strength and static strength is obvious on Fig. 11 and this result alone must affect the confidence with which we can accept the authors' asseveration that the fatigue strength of St. 52 is 10-15% better than St. 42. Dr L. D. Ivanov, Head of the Department of Naval Architecture at the Higher Mechanical Electrotechnical Institute in Varna, Bulgaria quoted fatigue data published by Professor V. V. Kozliakov(52) during discussions at Newcastle University.

For a series of sister ships the following data are given:

TABLE III

Type of steel	Length of ship (m)	$\frac{t_o}{t_o + t_r}$
mild	138	0·93
mild	120	0·93
H.T.	156	0·80
H.T.	115	0·61

where t_o = time in operation
t_r = time under repair

This corroborates the generally held view that higher strength steels offer no additional fatigue strength.

It has generally been recognised among civil engineers that the most advanced fatigue design rules are embodied in BS153. The commonest criticism of them is that they are too complicated when compared with American and Continental codes. This is a reflection of the fact that fatigue is a complex problem, but nevertheless it is important to strike a reasonable balance between accurate complexity and inaccurate simplicity. The Welding Institute has recently made tentative new proposals(53) which are clear, simple and statistically significant. They presuppose, of course, a safe-life philosophy, but this does not preclude a fail-safe approach as well.

REFERENCES

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Mr M. M. El Gammal, M.Sc. (Member): The work presented in this paper summarises the efforts that have been carried out in the field of fatigue in ship structural components. I would like to congratulate the authors for this intensive piece of work which is a major contribution to the rational design of ship structures against fatigue cracks.
However, there are some points raised in this paper which need further clarification. For example was the optimistic idea about the advantage of using higher strength steel over mild steel based on crack propagation considerations or the total number of cycles to failure? For instance the work carried out in Ref. 54 involved tests which have been carried out using both mild and high strength steels. Table IV shows the dimensions and the mechanical properties of the plate material considered in this investigation. The results are plotted in Fig. 30. From this figure, Fig. 31 was produced. From Fig. 30 it may be concluded that the total number of cycles to failure of the high strength steel is higher than that of the mild steel, though the crack propagation period for both was found to be nearly the same, see Fig. 31.

Also the problem of residual stresses due to welding and the different fabrication processes has been dealt with in a more qualitative rather than quantitative way. The authors noticed that residual stresses are more important for crack propagation than for crack initiation, which may raise the following question in the minds of the design engineers: does it mean that the safe-life concept must be applied in welded structural ship components? A fracture criterion which includes the effect of residual stresses is therefore needed so as to explain and to help in understanding the fatigue fracture problem.

A great deal of research work has to be carried out in order to correlate the mass of data presented in this paper with that gained from experience. Most of the fatigue crack propagation equations which have been derived so far take into account only the geometry and load factors(55). The material properties (e.g. the modulus of elasticity, the yield stress of the material and the fracture toughness index parameter) and the environmental conditions (e.g. the stress rate and the strain rate) have been difficult to take into consideration in the Paris-Erdogan equation. Apparently the previously mentioned factors have been included in the material constant 'C' in equation (1)(55):

$$\frac{da}{dN} = C[\Delta k]^m \qquad (1)$$

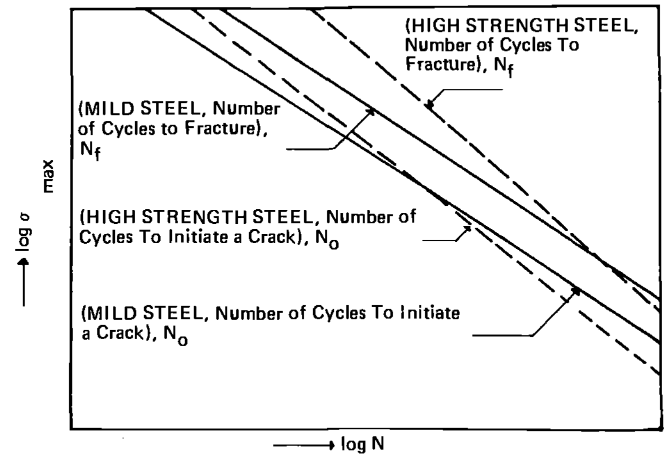

Fig. 30 Crack Initiation and the Total Number of Cycles to Failure for Mild and High Strength Steels, Ref. 54

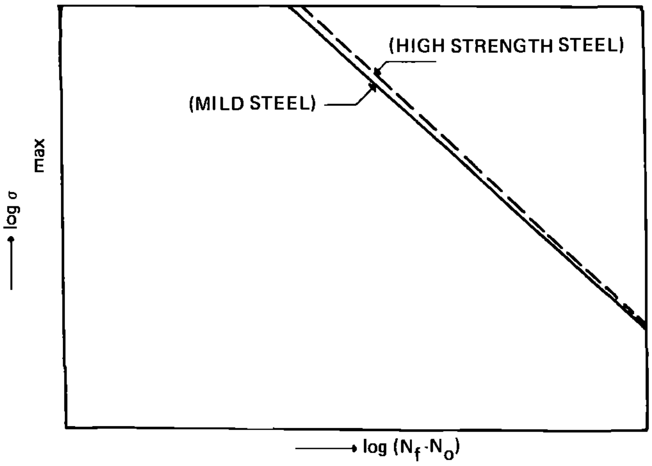

Fig. 31 Crack Propagation Periods for Mild and High Strength Steels

In order to relate the factor 'C' to the different parameters stated above, equation (2) has been assumed(56):

$$C = f(Y, E, K_c, m) \qquad (2)$$

where

Y is the yield stress of the material

E is the modulus of elasticity

K_c is the fracture toughness index parameter measured at a certain temperature and in a specified environment

m is the exponent in the relationship $N = \gamma\ \sigma_R^{-m}$, Fig. 32

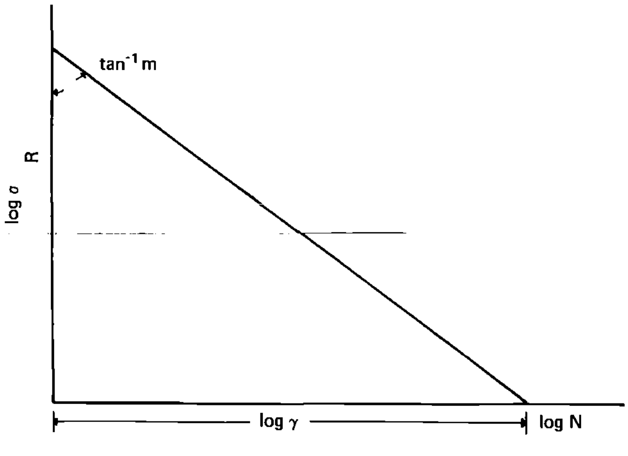

Fig. 32 Definition of Notation used in the Relationship $N = \gamma\ \sigma_R^{-m}$, Ref. 56

σ_R is the stress range

N is the corresponding number of cycles to failure

and

γ is the intercept, or the endurance at a stress range equal to unity.

Using dimensional analysis one can obtain equation (3):

$$C = \frac{1}{EY[K_c]^n} \qquad (3)$$

TABLE IV Material Properties and Dimensions for the Plates Used in Tests, Ref. 54

	Material Properties and Plate Dimensions	
Item	**Mild Steel Plates**	**High Strength Plates**
Modulus of Elasticity	$2 \cdot 14 \times 10^4 (kg/mm^2)$	$2 \cdot 12 \times 10^4 (kg/mm^2)$
Yield Strength	$27 \cdot 2 (kg/mm^2)$	$56 \cdot 6 (kg/mm^2)$
Breaking Strength	$46 \cdot 2 (kg/mm^2)$	$64 \cdot 8 (kg/mm^2)$
Elongation	39·0%	28·8%
Reduction of Area	71·5%	77·6%
Length × Width × Thickness	820(mm) × 200(mm) × 20(mm) or 12(mm)	820(mm) × 200(mm) × 17(mm) or 12(mm)

where 'n' in equation (3) has value of 'm-2'. Hence:

$$\frac{da}{dN} = \frac{[\Delta k]^m}{EY[K_c]^{m-2}} \qquad (4)$$

In order to check the validity of the value of the constant 'C' given by equation (3), a plot has been made from Fig. 16, as shown in Fig. 33. The values of Y, K_c and E for grade E steel have been used. Fairly good agreement is apparent although equations (3) and (4) were produced for a variable amplitude of cyclic loading.

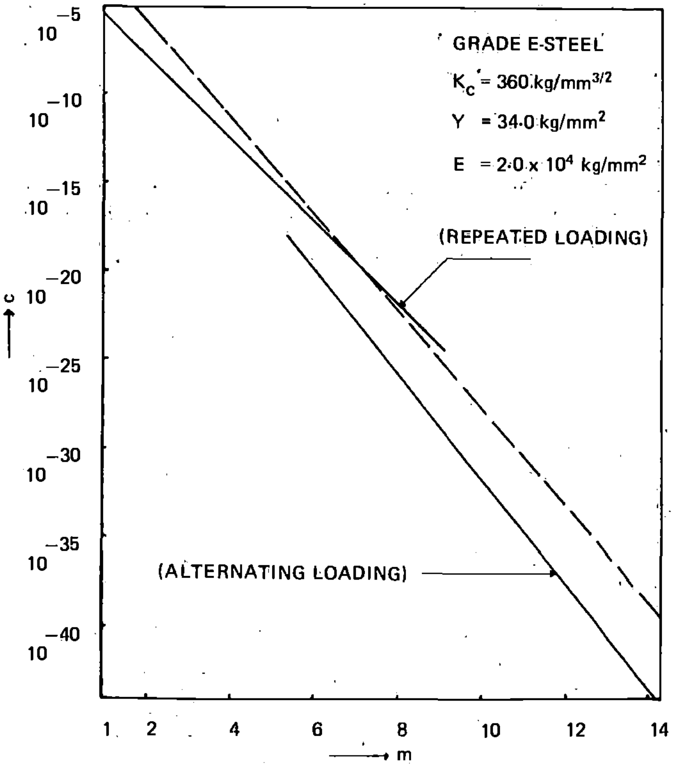

Fig. 33 Plot of Estimated C Value Obtained from the Relationship $C = \frac{1}{EY[K_c]^{m-2}}$ Against that Obtained experimentally, see Fig. 16

Though the Paris-Erdogan law, equation (1), has been derived for constant amplitude stress cases, it has been applied to variable amplitude stress spectra. Perhaps this may be due to the simplicity in using this law, which incorporates Miner's Rule of cumulative crack growth. A modification to the linear cumulative crack growth idea was proposed by Wheeler(57), for improving the accuracy of crack growth predictions in metal subjected to variable amplitude cyclic loading. This modification incorporates a consideration of prior load history by taking into account the yield zone ahead of the crack tip. The question now is, could Wheeler's model be applied to ship structural components? In the writer's view, if the fail-safe concept is to be applied, then one must take into account the effect of the loading history in the estimation of the fatigue life of cracked ship structural components.

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56. El Gammal, M. M.: 'A New Method for Estimating the Fatigue Life of Ship Structures'. Departmental Report, Department of Naval Architecture and Shipbuilding, The University of Newcastle upon Tyne, 1975.

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AUTHORS' REPLY

It is encouraging that Mr Taylor agrees to a large extent with the contents of the paper. Support for the idea of having standard loading patterns is particularly welcome when it comes from a classification society expert. The difficulty in connection with an 'average' behaviour is that an assumed 'average' programme may in reality be a rather mild or a severe one. Only after testing of an appreciable number of alternatives may we know the real value. Another—more conservative—approach would be to stipulate a 'severe' programme. This is easier to do with the existing knowledge. The probability that a ship will be loaded more or less in conformity with that programme can be determined by loading experts.

The safety of ships depends to a large extent on the resistance of ship materials to brittle fracture. Mr Spuyman is concerned about the danger of brittle fracture when fatigue is involved. Fortunately the chance that a brittle crack will start at a fatigue crack is very small. The reason is that not only are extreme conditions from the viewpoint of temperature and loading required, but also an extremely low quality of material at the crack tip. The latter depends very much on the position of the tip. Generally, only during a small percentage of the lifetime of the ship will a crack be situated in material of eventually low quality in the welded region, (see Fig. 5). The combined probability of occurrence of the latter and extreme weather conditions is very small. It may be calculated with the aid of Wöhler-curves for small crack lengths and weather data. It is thought that the curves for 5 mm crack length are useful in this respect(8).

Mr Spuyman's question about flame cut edges is very timely because only recently we have found the answer. With modern flame cutting machines edges with very good fatigue strengths may be obtained. Fatigue strength drops appreciably when defects are present, but only in special cases is there a need to remove these by local grinding (never by weld-repair). More information may be found in a paper presented during the joint RINA/Welding Institute conference(58). Fig. 23-g was a little misleading in the advance copy because only one loading block was indicated instead of one for each voyage, as was the intention. This has now been rectified. The observations of Professor Lewis support our general views in connection with fatigue. This is particularly welcome, because Professor Lewis has always had an open eye for structural design philosophy, next to his important work in connection with ship loads. Already in 1958 he and Dr Gerard edited the book 'A long range Research Program in Ship Structural Design', in which fatigue appeared as one of the important research objects.

Professor Aertssen's contribution paves the way for a confrontation of our experimental results with practical experience. This indeed is still a missing link! The calculated mean stresses in his Table II vary considerably which justifies the emphasis laid on these in the paper. For the ore carrier the situation in the loaded condition corresponds to repeated loading ($R = 0$), while in the ballast condition it is alternating loading ($R = -1$). We had not expected that a difference in draught of no more than 4 ft in a container ship would be accompanied by changes of mean stress from $+3{\cdot}1$ to $+8{\cdot}1$ kg/mm^2. For such cases the use of the higher strength Steel 52 is of course strongly recommended. It is fortunate that both ships have not suffered from fatigue, but for the purpose of scientific analysis it constitutes a drawback! It would be of great interest to know in which of the ships fatigue cracks are found first; we hope Professor Aertssen will keep us informed and that similar information will be given by Mr Huré of Bureau Veritas, when the investigations concerned permit this.

The next point is whether the good performance of both ships is in accordance with what might be predicted from our data. Following Professor Aertssen's approach we may plot at $2{\cdot}5 \times 10^4$ cycles the range values of Table II in Fig. 13 ($R = 0$; 5 mm crack length; curves 1), Fig. 20 ($R = \frac{1}{2}$; 5 mm) or Fig. 21 ($R = -\frac{1}{2}$; 20 mm). In Fig. 13 for curves 1 a value of 125 N/mm^2 is found at $2{\cdot}5 \times 10^4$ cycles. For the ore carrier the corresponding value is 123 N/mm^2. From this it may be concluded roughly that cracking will not occur during the ship's life. One could infer that cracks would appear sooner in the container ship, but it may be assumed that the structural configuration is of higher quality than that represented by the bracketed A-type specimen. But even for the latter type of structure there is no need for great concern because the data are valid for 5 mm crack length. In Fig. 14 it can be seen that a change of critical crack length from 5 mm to 20 mm ($\doteq$500 mm^2) allows an increase in permissible stress level of some 25 N/mm^2 leading to $125 + 25 = 150$ N/mm^2. This value is close to those of Table II for the containership (16·2 and 15·8 kg/mm^2). But, as Professor Aertssen suggests, the use of St. 52 in the container ship is largely responsible for her good performance. The loading of that ship conforms well to the type which in the experiments gave far better results for St. 52 than for St. 42.

We strongly support Mr Christopher's wish for information about fatigue-cracking in ships. Exaggerating the situation a little we might say that in the few cases that we are informed about numbers and lengths of cracks, we know little or nothing about the loads the particular ships have met in their lives. But mostly the reverse is true: we often know a lot about the loads but little about the fatigue performance. Professor Aertssen has made a step in the right direction in giving information from both sides. Mr Christopher's suggestion for monitoring fatigue cracks is the best thing to do. It will probably be done in the near future in offshore structures. Mr Christopher's observation about the importance of a high yield stress for any type of failure is supported by the results of the experiments at low temperature. Brittle fractures could only develop after the nominal stresses became equal to yield point, (test temperature −35°C).

The application of fracture mechanics in order to relate results of small simple specimens with those of large structural ones has been promising. It seems advisable to use as significant stress values those which exist fairly close to the crack origins. We have called them 'local nominal values'. In Fig. 18 they are the values obtained from gauges 2; the corresponding curves are indicated by the roman number II. For reasons of available time and money we have not been able to calculate the stress distributions in the specimens with the aid of finite elements. Yet is is the only possible method for obtaining reliable stress intensity values for different crack lengths in complex structures. On the other hand, when Fig. 19 is studied, one may doubt the need for great accuracy in stress calculations. For even for such well-defined cases as bending and axial loading of plate specimens with $R = 0$, fracture mechanics did not help to bring the curves I and III close together. The statement about fine grain steels has been made in connection with high heat-input welding. For instance one-pass Electrogas and Electroslag welding may give rise to extreme grain coarsening in the parent metal adjacent to the fusion line. The width of that zone is only 2 or 3 mm. The notch toughness is extremely low. Charpy transition temperatures of +20°C to +40°C at 3·5 kgm/cm^2 are quite normal. In such cases a small transverse weld crack, extended by cyclic loading, may give rise to brittle fracture as long as its tip is situated in the coarse grained zone. But as soon as it has left the zone it enters a region of high toughness and may grow over the whole plate width without endangering the ship. The point has been illustrated in Fig. 5. The relevant experimental results can be found in Ref. 12.

Professor Telfer is right when he has understood from the presentation that a welded overlap is thought to be equivalent to a crack. But in agreement with him I mentioned it as an example of what may exist in ships without danger. An extreme example of how far shipbuilders and owners went on this way in the past are expansion joints in deckhouses of passenger ships. It may interest Professor Telfer that although an important part of our work is devoted to welding, the modern form of riveting (being bolting) may sometimes constitute a safer method of connecting structural parts, especially in difficult circumstances. We particularly think of erection of offshore structures at sea. Friction forces between plates are responsible for high joint efficiencies, while at the same time guaranteeing flexibility. The problem with grinding of sharp corners in test specimens is that on one hand it greatly reduces scatter, and so the required number of specimens, but on the other hand makes the specimens less realistic. Our approach has been to simulate average shipbuilding practice.

We do not feel that Professor Steneroth and ourselves are really of different opinions. It is more a matter of emphasis. Maybe the consequences of both possible approaches are most serious for the attitudes people take in connection with cracks. When cracks are accepted in design they will gradually also be looked upon as normal things in practice. Then it may save costs in both ways: lighter structures and fewer repairs. Professor Steneroth has made thorough contributions to the problem of fatigue in shipbuilding, both in the ISCC and in the RINA. His eight year old conviction (or older) that a better fatigue life must be expected for the high tensile steel structure has been well confirmed by the results given in our paper, despite some conflicting data. Our statement that there will be faster crack propagation the longer the initiation time has two aspects. The first is that in a smooth specimen a fatigue crack can only start after a high number of load cycles which will cause fatigue damage of the uncracked material. Due to that the resistance to crack propagation of that material will be reduced and the crack will propagate faster than in metal which has been less damaged prior to crack formation. In fact Miner's Rule is based on similar considerations.

Of course the whole fatigue life of a smooth specimen will be many times larger than that of a severely notched one. We fully agree with Professor Steneroth that it pays to streamline and grind important structural details like hatch corners. It is always difficult to say that one is glad to hear that fatigue cracks have been found in a ship. But in the case Dr Johnson mentioned, viz. the OCEAN VULCAN, our satisfaction may be interpreted in another way, namely that the ship has proved that cracks are mostly unharmful, for the OCEAN VULCAN—as so many others—has not fractured in two.

For offshore structures the crack-design philosophy may indeed be followed less consequently than for ships as Dr Johnson suggests. This is not only connected to less redundancy, but also to inspection difficulties.

It is particularly fortunate that Professor Petershagen and Mr Paetzold have continued their part of the programme beyond their contractual obligations. It is of great interest that their results confirm the m-log C relationship of the Belgian data. The fact that m is not constant over the whole cracking period is certainly partly caused by the neglection of the plastic zone size at high Δk values. But when appropriate corrections are made, the curves for lower and higher Δk values do not come completely in line. Apparently other factors, like strain hardening or softening also play a role. It is hoped that Professor Petershagen—who has largely stimulated the co-operative effort and contributed actively to the philosophical background—and Mr Paetzold will soon be able to publish their new results.

Professor Marsich has been so kind to give some information about that part of the co-operative investigation, which due to unforeseen difficulties during the testing, could not be included in the paper. With some caution, the results of the Italian test programme may be plotted in Fig. 20 for $R = -\frac{1}{2}$. Then they should be compared with the curves numbered 2 of the French bracketed specimens and the brackets of the Dutch specimens. It can be concluded that the difference in structural design between the Italian specimens and those of Fig. 20 is responsible for a difference in level of permissible stresses by a factor of at least 2.

Mr Huré is in a better position than most designers when a method has to be chosen for the calculation of the fatigue life of a ship. He has the great advantage of information about the fatigue performance of ships. It is our conviction that, for the time being, a simple calculation method regularly adjusted by feedback from practical experience is more reliable and thus valuable than a more sophisticated procedure totally based on theories and laboratory investigations. This is in line with Mr Christopher's opinion which might be translated into: there is no better laboratory than the sea and no better specimen that an actual ship. It is hoped that his, and our, wish for data obtained in practice will be met by Bureau Veritas and of course by the other classification societies. Mr Huré's third point in which the rapid crack growth caused by a few severe weather voyages is noted is of particular interest to us, since the simple test programme of Fig. 7 includes a part which represents very bad weather (50 cycles of 185 resp. 222 N/mm^2). In Delft we are now carrying out experiments with a programme in which these high loads have been excluded in order to see whether the shifting of the mean stresses or these high loads was responsible for the large difference between St. 42 and St. 52. Mr Soejadi asks why random loading for fatigue testing is not advisable in the case of ships. In the extreme, random loading is completely undefined. But that is not of interest for ships because we know that seawaves obey certain statistical laws. For ships we can speak about stochastic loading which consists of loading cycles conforming to certain statistically definable distributions. The sequence of these cycles may be seen as random.

It is the same as saying that the phase-differences between the sinusoidal components of a certain wave spectrum are completely random. Another objection is that a ship acts as a filter with respect to the loads caused by sea waves. A ship is more than a puppet in the hands of the sea. This applies to classic longitudinal bending but also, and very clearly, to springing. On the other hand wave spectra are different in shape for different parts of the world.

Finally, ships are handled by men who consciously or subconsciously react upon the wave loads, slamming, springing, vibrations etc. by changing course or reducing speed. The authors are grateful for Mr Soejadi's observations in connection with changes of still water stresses. They show that we did not exaggarate when stating that these changes form an important part of the total load system. Of course for the sake of argument we had to simplify the loading state.

Dr Ractliffe is right when he asks for more information about scatter of the experimental results. In the present paper we preferred to deal with the state of affairs rather than giving exhaustive data. These can be found in Ref. 8, especially in Appendix III. A full statistical treatment, however, is hardly possible for experiments concentrated on crack propagation. One problem is how to distinguish between scatter inherent to fatigue testing, and scatter caused by possible inaccuracy in fabrication of structural specimens, observation of crack growth, personal care in evaluating experimental results etc. We preferred to treat our experimental data in such a way that by cross-referencing and combining individual data, the utmost reliability and accuracy of the crack propagation curves was obtained. Deviating results were related to the geometry of the specimens and their welds and fatigue crack configuration. The point in connection with Fig. 11 is not convincing. Firstly the figure ends at 1000 cycles and not at $\frac{1}{2}$. Secondly it is thought to be wrong to apply a form of curve-fitting which might violate the experimental results. These should be presented as they have emerged from experiments and analysis.

The greatest merit of fatigue design rules is that they offer a basis for comparisons between alternative designs. Whether or not the predicted fatigue lives are real is often of secondary importance. Most of the structures designed with the aid of these rules will be quite safe, even too safe; a few will give trouble. This gives evidence that the rules do not incorporate all relevant parameters. But as long as everybody has to work with them, nobody will feel unhappy. This is one of the reasons that Miner's Rule is still popular. Dr Ractliffe will immediately admit that there is an enormous difference between the loading of bridges on one hand and of marine structures on the other hand, yet BS 153 is gaily applied to the latter. The main objection to it is that many structural designers believe that the calculated result is real, while it is ficticious.

In reply to Mr El Gammal's first question, attention is drawn to Figs. 14 and 15. From these it is clear that the advantage of St. 52 over St. 42 is caused by the better resistance to crack propagation of the former. The Belgian results for unwelded notched plates permit the same conclusion.

Concerning the influence of residual stresses it has been stated in the paper that they may have an adverse effect, particularly in the early stages of crack development. The intention was to say that this effect will be felt as long as the crack is present in the—generally small—region of tensile residual stresses. This includes the stage of micro-cracking and so the crack initiation period. On the other hand a fracture calculation should also take into account that soon after crack development compressive residual stresses may often exert a beneficial influence.

Mr El Gammal's adjustment of the crack propagation formula to material parameters leads to a surprisingly good agreement with our data in Fig. 16. We certainly will apply this treatment to other experimental results. We agree with Mr El Gammal that prior load history should be taken into account when estimating fatigue life. But Miner's Rule is already a kind of cumulative damage rule. Maybe some shortcomings of the rule mentioned in the paper in connection with crack propagation are more or less met in Wheeler's model. But in our opinion for the crack propagation stage an approach basically different from Miner's should be found.

REFERENCE

58. Nibbering, J. J. W.: 'Is there a need for postcutting treatments in shipbuilding?' Paper 5 Procs. Structural Design and Fabrication in Shipbuilding. London, November 1975, RINA and The Welding Institute.